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A.B. Forman

MASTER

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SEFOR CORE I TEST RESULTS TO 20 MW

L.D. NOBLE et al

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SEFOR CORE I TEST RESULTS TO 20 MW

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ABSTRACT

The Southwest Experimental Fast Oxide Reactor (SEFOR) is a fast spectrum reactor fueled with mixed $\text{PuO}_2\text{-UO}_2$ and cooled with sodium. The reactor was designed to enable the determination of the Doppler coefficient at fuel temperatures up to the vicinity of fuel melting, and an experimental program was planned for Core I that begins with a series of tests at low power, proceeds through static and oscillator tests at various power levels up to full power (20 MW), and culminates in a series of sub-prompt and super-prompt critical transients. A similar test program is planned for a second core (Core II) with a somewhat harder neutron spectrum.

The results of static and oscillator tests performed at power levels up to 20 MW and at fuel temperatures up to approximately 4800°F during the power ascension phase of the experimental program in SEFOR Core I are reported here, and are compared with calculations. The experimental results are in agreement with calculations at all power levels, and preliminary analysis of data indicates that the SEFOR Doppler coefficient $T \frac{dk}{dT}$ is -0.0081 ± 0.0014 (estimated standard deviation). This coefficient compares favorably with the value of -0.0085 that was predicted prior to the experiments.

SECTION 1

INTRODUCTION AND SUMMARY1.1 INTRODUCTION

This report describes results and analyses of experimental data taken during the power ascension phase of the planned SEFOR experimental program for Core I, and includes a preliminary evaluation of the SEFOR Doppler reactivity effects at power levels up to 20 MW.

The Southwest Experimental Fast Oxide Reactor (SEFOR) is a 20 MW fast spectrum reactor fueled with mixed $\text{PuO}_2\text{-UO}_2$ and cooled with sodium. SEFOR has characteristics similar to large, soft spectrum, fast breeder reactors fueled with mixed $\text{PuO}_2\text{-UO}_2$ for economic electrical power generation. SEFOR is being used to obtain physics and engineering data at fuel compositions, temperatures, and crystalline states characteristic of power reactor operating conditions. The reactor is particularly designed for the systematic determination of the Doppler coefficient of reactivity at temperatures up to the vicinity of fuel melting.

The SEFOR project consists of two major parts: the design and construction of the reactor and a related research and development program. Funds for the design and construction of the facility were provided by the Southwest Atomic Energy Associates (a group of seventeen investor-owned utility companies located in the South and Southwest part of the United States), together with the Karlsruhe Laboratory of the Federal Republic of Germany, Euratom, and the General Electric Company.

The United States Atomic Energy Commission is supporting the research and development program. The R and D Program consists of two phases:

- Phase I - Pre-Operational Research and Development
- Phase II - Post Construction Research and Development

Work performed in Phase I of the program under Task 1, planning the experimental program, has been reported in references 1 through 4. The SEFOR facility is described in references 5 and 6, and the physics design of the core is described in references 6 through 9. The objectives of the

SEFOR experimental program are to:

- a. Investigate the operating characteristics of sodium-cooled, mixed $\text{PuO}_2\text{-UO}_2$ fueled fast spectrum reactors.
- b. Investigate and measure the Doppler reactivity effect during normal reactor operating conditions.
- c. Investigate and measure the Doppler reactivity effect during abnormal reactor transient conditions, and in particular, to determine its relation to inherent reactor shutdown capability.

The experiments which have been planned to meet these objectives are described in detail in Reference 4. These tests may be broken down into the following four broad classifications: 1. zero power tests, 2. static tests, 3. oscillator tests, and 4. transient tests.

1. The zero power tests are conducted at low (zero) power and include conventional tests such as the approach to critical, control rod calibration, power distribution measurements, and material worth measurements. In addition, these tests provide for the measurement of the isothermal temperature coefficient of reactivity by using an external (non-nuclear) heat source, and for measurement of the ratio (ℓ/β) of the prompt neutron lifetime to the delayed neutron fraction by noise analysis methods.
2. In the static tests, the reactor is operated at a steady-state condition at a number of different reactor conditions (i.e., at different power levels, flow rates, and coolant inlet temperatures). The planned test conditions were selected so that the "static" reactivity effects associated with 1) a change in power at constant average coolant temperature, 2) a change in average coolant temperature at constant power, and 3) a change in inlet temperature at constant power and average coolant temperature, can be separately determined.
3. In the conventional oscillator tests a B_4C rod is oscillated at several frequencies and the reactor power and coolant temperatures are allowed to oscillate about their mean value. These oscillations serve to demonstrate reactor stability, and a comparison of measurements at power levels ≥ 2 MW with those at low (~ 600 W) power provides for determination of the time response of the reactivity feedback. In the balanced^(3,10) oscillator tests a B_4C rod, the primary coolant

flow, and the secondary coolant flow are simultaneously oscillated in an attempt to separate the fuel temperature reactivity effects from the coolant temperature reactivity effects.

4. The transient tests include sub-prompt critical tests (rapid insertion of $< \$1.0$ positive reactivity) and super-prompt critical tests (rapid insertion of $> \$1.0$ positive reactivity). These tests are performed at different initial power levels and will allow determination of the reactivity-energy coefficient over a range of fuel temperatures.

The Doppler reactivity coefficient will be determined on two different cores. The first core (Core I) contains BeO to soften the neutron spectrum and increase the magnitude of the Doppler effect. In the second core (Core II) the BeO will be replaced by stainless steel with a consequent hardening of the neutron spectrum and a reduction in the magnitude of the Doppler coefficient.

The zero power tests for SEFOR Core I were performed⁽¹¹⁾ in Phase II of the program under Task 10.3, Wet Critical Tests. The results of these tests showed⁽¹¹⁾ good agreement between calculations and experimental data.

This report describes work performed in Phase II of the program for SEFOR Core I under Task 10.4, Approach to Power. The results reported here include the static and conventional oscillator tests at power levels up to 20 MW.

1.2 SUMMARY OF RESULTS

Measurements of the reactivity feedback in SEFOR were performed at power levels up to 20 MW and at average coolant temperatures between 350°F and 760°F. During these measurements the mixed oxide ($\text{PuO}_2\text{-UO}_2$) fuel temperatures ranged between a minimum of 350°F and a calculated maximum of approximately 4800°F. The time dependent reactivity feedback was determined from the frequency response of the system to sinusoidal oscillations in input reactivity, and the changes in reactivity between different steady state conditions were measured over the complete range of power and coolant temperature conditions.

The experiments have shown, in agreement with calculation,⁽¹¹⁾ that the only significant reactivity effects are those associated with changes in the average core coolant temperature and with changes in the fuel temperature. Since the SEFOR fuel was designed⁽⁶⁾ to suppress fuel axial expansion reactivity effects, most (~95%) of the reactivity effect due to fuel temperature changes is the result of Doppler broadening of the nuclear cross sections. Analysis of the data and comparison of results with calculations indicates that the SEFOR Doppler temperature coefficient $T \frac{dk}{dT}$ is -0.0081 with an estimated standard deviation of ± 0.0014 . This coefficient compares favorably with the value^{*} of -0.0085 that was predicted⁽¹¹⁾ prior to the experiments.

The primary contributor to the estimated standard deviation of ± 0.0014 ($\pm 17\%$ in the Doppler value of -0.0081) in the Doppler temperature coefficient is a $\pm 15\%$ uncertainty in the fuel temperature-power relationship as a result of a $\pm 15\%$ uncertainty in fuel thermal conductivity. Although actual SEFOR fuel temperature measurements were used to minimize the effects on the Doppler measurements of uncertainties in other

*This is the estimated prediction for the cores, Assemblies I-I and I-J (the present core), on which these Doppler experiments were performed. The actual prediction, for a core with 19 B_4C rods, was -0.0082. The predicted effect for a core with 12 B_4C rods was -0.0085.

parameters such as the fuel to cladding heat transfer coefficient, the measurements do not appear to be sufficiently accurate over a wide range of power levels to eliminate the effects of uncertainties in fuel thermal conductivity. The estimated standard deviation in the Doppler effect would be reduced to $\pm 8\%$ (see Section 6.5 for detailed components) if the uncertainty in the power-fuel temperature relationship could be eliminated or reduced to insignificant proportions. Qualitatively, it appears that some of the fuel temperature data shown in Section 2 might support an uncertainty estimate of $\pm 13\%$ in the Doppler $T \frac{dk}{dT}$.

The Doppler components of the measured reactivity feedback effects are summarized, and compared with the effects calculated using a Doppler temperature coefficient $T \frac{dk}{dT}$ of -0.0081 in Table 1-1. The values in the table show that there is good agreement at all power levels between the measured and calculated values of the integral Doppler reactivity effect, and that there is an overall agreement among the power coefficients determined from the oscillator tests, static tests, and from calculations. The general agreement between calculated and measured time dependent characteristics of the system are illustrated by the measured and calculated fuel time constants.

Effects of fuel pellet changes (cracking, etc.) on power-reactivity effects were observed to be small. (Thus, Table 1-1 shows only one value of ΔK vs. power).

TABLE 1-1

SEFOR DOPPLER MEASUREMENTS

Power Level (MW)	Total Integral Doppler Effect		Power Oscillator Tests (¢/MW)	Doppler Reactivity Coefficient		Fuel Time Constants	
	Static Tests (¢)	Calculated (¢)		Static Tests (¢/MW)	Calculated (¢/MW)	Oscillator Tests (sec)	Calculated (sec)
0	0	0	-	-16.8±1.7	-	-	-
2	-31±2	-36	-15.8±1.3	-14.4±1.2	-15.5	30.1±2.2	32.6
5	-71±5	-75	-10.9±0.9	-11.6±0.8	-11.1	28.0±2.2	31.6
10	-120±8	-120	- 8.3±0.7	- 8.5±0.6	- 7.6	28.7±2.2	29.0
15	-156±10	-154	- 5.7±0.7	- 6.5±0.6	- 6.0	28.0±2.2	27.5
17	-172±11	-167	- 5.0±0.6	- 5.9±0.6	- 5.6	26.7±2.2	27.0
19	-182±12	-177	- 4.2±0.6	- 5.4±0.7	- 5.1	24.5±2.2	26.5
20	-187±12	-182	-	- 5.2±0.8	- 5.0	-	-

Calculated results are for a Doppler temperature coefficient $T \frac{dk}{dT}$ of -0.0081.

SECTION 2

IN-CORE TEMPERATURE MEASUREMENTS

2.1 FUEL TEMPERATURE MEASUREMENTS

Fuel temperatures have been measured at up to seven different core locations at power levels up to 20 MW. The early fuel temperature measurements at power levels up to 5 MW were used to normalize the model used for fuel temperature calculations. This was accomplished by adjusting the fuel-clad heat transfer coefficient to provide agreement between measured and calculated temperatures. Since the adjusted fuel-clad gap coefficient agreed reasonably well with the calculated value, the normalized model was then used to predict fuel temperatures at higher power levels.

Only one fuel-clad heat transfer coefficient was required to adequately describe all the early fuel temperature measurements at the seven core locations. The normalization of the fuel temperature calculational model and the comparison of predicted and measured temperatures at higher power levels are discussed below. The use of this model to determine the power-fuel temperature relationship necessary for a comparison of measured and calculated Doppler reactivity effects is discussed in Section 6.

2.1.1 FUEL TEMPERATURE INSTRUMENTATION

Fuel temperatures were measured at seven different core locations. The temperature sensing devices are W-Re thermocouples (T/C's) that are described in references 1 and 2. The thermocouples are located along the center line of four different fuel rods in two instrumented fuel assemblies⁽³⁾ (IFA's). All of the fuel thermocouples are located at one of two axial positions; either 2 1/4 inches or 15 1/2 inches above the midplane of the 36 inch high core. Those near the midplane are referred to

as lower T/C's, while those 15 1/2 inches above the midplane are referred to as upper T/C's. One IFA was located near the core center line, and one near the periphery as shown in Figure 2-1. Each IFA contains an "inner fuel rod" and an "outer fuel rod", with the inner rod being that closest to the core center line. See Table 2-2 for T/C physical characteristics.

2.1.2 NORMALIZATION OF THE MODEL

The initial fuel temperature measurements from the seven T/C's are listed in Table 2-1. The eighth position, i.e., the upper T/C in the outer fuel rod of the peripheral IFA, was used as a "dummy thermocouple" in order to observe any spurious background signals; there were none. As indicated in Table 2-1, the measured differences between the fuel temperatures and sodium temperatures at all locations demonstrated an approximately linear dependence on power during initial operation at power levels up to 5 MW. The average increases per megawatt power change, i.e., the slopes of the straight line fuel temperature-power relation, are tabulated in Table 2-1. The ratios of these slopes are compared in Table 2-2 with the ratios of local fuel rod power densities obtained from the calculated power distribution, including corrections, that is described in reference 4. The general correlation between the local power densities and the magnitudes of the local changes in temperature at the different thermocouple locations indicated that one and the same model could be used to calculate all fuel temperatures in the core. The normalization of this model to the early 5 MW data is described below.

The actual local Pu enrichment was taken into consideration in determining the power density ratios shown in Table 2-2. The enrichment at all thermocouple locations in the peripheral IFA was 20.4% Pu/U+Pu, while the enrichment in the outer rod of the central IFA was 18.8% Pu at both thermocouple locations. The enrichments at the upper and lower locations of the inner rod of the central IFA were 18.1% and 17.6% Pu respectively.

Using the best estimate of fuel thermal conductivity, power density, rod dimensions, thermal properties of the clad and coolant, etc., the fuel to clad heat transfer coefficient was adjusted to provide agreement between calculated central fuel rod temperatures and the temperatures measured during initial operation at power levels up to 5 MW. The fuel to clad heat transfer coefficient, rather than some other parameter, was used to

FIGURE 2-1 INSTRUMENTED FUEL ASSEMBLY (IFA)
LOCATIONS IN ASSEMBLY I-I

TABLE 2-1

INITIAL IFA FUEL TEMPERATURE RISE

POWER	FUEL TEMPERATURE RISE ABOVE THE SODIUM TEMPERATURE**							
	<u>CENTRAL IFA</u>				<u>PERIPHERAL IFA</u>			
	Inner Fuel Rod		Outer Fuel Rod		Inner Fuel Rod		Outer Fuel Rod	
	Upper* T/C	Lower T/C	Upper T/C	Lower T/C	Upper T/C	Lower T/C	Upper+ T/C	Lower T/C
(MW)	(°F)	(°F)	(°F)	(°F)	(°F)	(°F)	(°F)	(°F)
0	0	0	0	0	0	0	-	0
0.4	52	82	-	85	35	68	-	56
0.8	75	135	-	137	61	104	-	90
1.0	108	166	105	176	77	133	-	116
2.0	197	-	192	329	140	246	-	208
5.0	471	822	477	864	-	636	-	529
Average Increase per Megawatt	94.4	165	95.8	172	75.0	127	-	106

* These are average values. This T/C was noisy with 20 to 30°F temperature fluctuations. The other T/C's demonstrated little or no fluctuations.

+ This is a dummy thermocouple (T/C) that is used to account for any spurious signals.

** The average sodium temperature ranged between ~740 and 760°F.

TABLE 2-2

RELATIVE FUEL ROD TEMPERATURES AND POWER DENSITIES

Relative Ratios	CENTRAL IFA				PERIPHERAL IFA			
	Inner Fuel Rod Upper T/C	Fuel Rod Lower T/C	Outer Fuel Rod Upper T/C	Fuel Rod Lower T/C	Inner Fuel Rod Upper T/C	Fuel Rod Lower T/C	Outer Fuel Rod Upper T/C	Fuel Rod Lower T/C
Average Measured Fuel Temperature Rises	0.57	1.00*	0.58	1.04	0.45	0.77	-	0.64
Fuel Rod Power Densities Based on Calculations	0.60	1.00*	0.60	1.02	0.41	0.72	0.37	0.63
T/C PHYSICAL CHARACTERISTICS								
Thermocouple Sheath OD (inches)	0.064	0.064	0.064	0.064	0.064	0.064	0.140	0.064
Thermocouple Insulation	BeO	ThO ₂	BeO	BeO	BeO	BeO	BeO	BeO
Thermoelement wire size (inches)	0.005	0.005	0.005	0.005	0.005	0.005	0.010	0.005

*Normalization point - The power density at this point is 80.5% of the peak power density in a normal standard fuel rod at the core center.

normalize the data, because it is the one temperature-influential-parameter in SEFOR that is least amenable to independent calculation or measurement.

The fuel thermal conductivity used in the normalization employed Schmits⁽⁵⁾ data for fuel temperatures less than 1100°F, and the following relationship⁽⁶⁾ for temperatures between 1100°F and 3000°F.

$$K = 0.011 + [T(0.4848 - 0.4465D)]^{-1}$$

where K is in units of watt/cm-°C, the temperature T is in degrees centigrade, and D is the initial fraction of theoretical pellet density. For the SEFOR IFA pellets D = 0.937. The clad to coolant heat transfer coefficient was taken as 5000 Btu/ft²-hr-°F, and the power distribution discussed in reference 4 was used. This distribution has a core peak to average power ratio of 1.76 and a core peak power density of 150 W/cm³ at 20 MW. The local power density at a given thermocouple location was determined from the following relation

$$\rho = \frac{150}{20} (0.805)PR$$

where ρ is the desired power density in W/cm³; P is the power level in MW; R is the appropriate power density from row two of Table 2-2; 150/20 is the ratio of peak core power density to the total reactor power; and 0.805 is the factor in the footnote of Table 2-2.

The values for the fuel to clad heat transfer coefficient obtained from analysis of the initial data through 7/11/70 at power levels to 5 MW can be expressed by the following polynomial

$$h = 130 + 1.75 \rho + 0.0277 \rho^2$$

where h is in units of Btu/ft²-hr-°F and ρ is in W/cm³. The coefficient obtained using this expression deviates from the expected coefficient by no more than 20% at power densities above ~30 watts/cc, but is 40% lower than expected at zero power. Fuel rod temperatures calculated using this expression with the fuel thermal conductivity, etc. described above are illustrated in Figure 2-2. Since the average fuel temperature at higher

FIGURE 2-2 FUEL ROD TEMPERATURE VS. POWER DENSITY

power levels is primarily determined by the thermal conductivity rather than the fuel-cladding gap coefficient (e.g. the difference between average and surface temperature in Figure 2-2 is only dependent on fuel conductivity), and since the fitted gap coefficient did not deviate greatly from the expected value, it was used in the fuel temperature and Doppler models described below.

2.1.3 COMPARISON OF MEASURED AND CALCULATED TEMPERATURES

The measured increases in fuel temperature with power are tabulated in Table 2-3. As indicated by the data in the table, one T/C (#17) was erratic after initial operation at 2 MW, and another T/C (#3) was erratic after initial operation at 5 MW. All of the data in Table 2-3 were taken with an average core sodium temperature of $\sim 760^{\circ}\text{F}$, except for those few measurements which are noted in the table.

Five of the fuel thermocouples are compared with the temperatures calculated using the model described above in Figures 2-3 through 2-7.

Good agreement between calculated and measured temperatures was observed for the thermocouples in the central IFA up to power levels of 10 MW or higher. Above 10 MW, T/C #2 became somewhat erratic as indicated by the data, while T/C #4 agreed with calculations for initial operation up to ~ 15 MW, but began to indicate lower fuel temperatures thereafter. T/C #1 has indicated slightly lower temperatures than predicted above the 5 MW power level, and considerably lower temperatures after the 20 MW operation. Subsequent to initial operation at 5 MW, Figures 2-6 and 2-7 show that fuel thermocouples #18 and 20 in the peripheral IFA increased above the predicted temperatures (even while the power level remained constant) and then, except for some lower temperatures for T/C #18 near 13 MW, remained above the calculated values. Prior to operation in early 1971, T/C #18 began indicating very low temperatures and these readings were not tabulated in Table 2-3. Except for T/C #20, which continues to indicate higher and higher temperature readings, all of the thermocouple readings have decreased over a period of time.

None of the thermocouples have recorded a temperature higher than $\sim 3000^{\circ}\text{F}$ to $\sim 3500^{\circ}\text{F}$, even though calculations indicate local fuel temperatures at some of the T/C locations may have reached $\sim 4000^{\circ}\text{F}$, and all thermocouples have shown a deterioration in performance over a period of time. These effects may have been caused by the thermal cycling, the high temperature

TABLE 2-3
IFA FUEL TEMPERATURES TO 20 MW

Fuel Temperature Rise Above Sodium Coolant Temperature of ~760°F								
Date (1970)	Thermal Power (MW)	Central IFA				Peripheral IFA		
		Inner Fuel Rod		Outer Fuel Rod		Inner Fuel Rod		Outer Fuel Rod
		Upper T/C #1 (°F)	Lower T/C #2 (°F)	Upper T/C #3 (°F)	Lower T/C #4 (°F)	Upper T/C #17 (°F)	Lower T/C #18 (°F)	Lower T/C #20 (°F)
7/2	0.4	52	82	-	85	35	68	56
7/2	0.8	75	135	-	137	61	104	90
7/2	1.0	108	166	105	176	77	133	116
7/3	2.0	197	-	192	329	140	246	208
7/9	5.0	471	822	477	864	-	636	529
7/9	5.1	475	816	487	870	-	641	541
7/10	5.2	507	824	487	862	-	640	540
7/10	5.1	507	824	487	860	-	646	544
7/10	5.2	495	822	477	875	-	643	534
7/11	5.0	466	760	446	808	-	608	506
7/23	5.0	472	804	-	830	-	702	574
7/24	5.2	448	737	-	753	-	662	540
7/27*	5.2	453	750	-	769	-	710	564
7/27*	5.4	467	780	-	799	-	734	585
7/27**	5.4	463	775	-	792	-	752	598
7/28†	5.8	503	842	-	861	-	835	658
8/6	2.2	199	294	-	317	-	344	282
8/7	5.2	470	790	-	803	-	808	664
8/14	4.9	454	770	-	773	-	831	678
8/14	6.0	554	962	-	964	-	991	832
8/14	7.0	640	1123	-	1044	-	1119	966
8/14	8.0	724	1289	-	1364	-	1254	1090
8/14	9.1	824	1490	-	1578	-	1360	1236
8/14	10.1	902	1671	-	1748	-	1506	1343
8/15	10.1	884	1435	-	1774	-	1669	1317
8/17	9.9	872	1390	-	1772	-	1704	1327
8/18††	10.0	841	1329	-	1772	-	1646	1279
8/23	5.1	436	651	-	-	-	967	754
8/29	10.1	898	1365	-	1756	-	1753	1427

*Average core sodium temperature is ~600°F.

**Average core sodium temperature is ~500°F.

†Average core sodium temperature is ~400°F.

††Average core sodium temperature is ~560°F.

TABLE 2-3 (Continued)
IFA FUEL TEMPERATURES TO 20 MW

Fuel Temperature Rise Above Sodium Coolant Temperature of ~760°F						
Date (1970)	Thermal Power (MW)	Central IFA			Peripheral IFA	
		Inner Fuel Rod		Outer Fuel Rod	Inner Fuel Rod	Outer Fuel Rod
		Upper T/C #1 (° F)	Lower T/C #2 (° F)	Lower T/C #4 (° F)	Lower T/C #18 (° F)	Lower T/C #20 (° F)
8/29	11.2	973	1525	1834	1728	1520
8/29	12.5	1076	2021	2306	1691	1643
8/29	13.2	1145	2144	2487	1554	1736
8/29	14.0	1213	2292	2834	1499	1825
8/29	15.5	1383	2559	2761	1820	1957
8/29	14.8	1329	2351	2703	2095	1903
8/30	14.8	1343	1337	1957	2099	1920
8/30	15.1	1352	1331	1239	2262	1948
9/4	9.9	852	847	1491	1690	1426
9/5	10.1	828	840	1564	1720	1425
9/5	15.0	1305	1325	1934	2214	1969
9/5	15.0	1290	1315	1818	2170	1960
9/5	17.2	1612	1340	1805	1898	2177
9/6	17.2	1561	1307	1270	2251	2182

TABLE 2-3 (Continued)

IFA FUEL TEMPERATURES TO 20 MW

Date (1971)	Thermal Power (MW)	Fuel Temperature Rise Above Sodium Coolant Temperature of ~760°F			
		Central IFA			Peripheral IFA
		Inner Fuel Rod		Outer Fuel Rod	Outer Fuel Rod
		Upper T/C #1 (°F)	Lower T/C #2 (°F)	Lower T/C #4 (°F)	Lower T/C #20 (°F)
1/25	5.1	365	310	599	864
1/26	10.1	764	655	1243	1579
1/26	14.7	1194	1008	1845	2099
1/26	15.6	1255	1078	1952	2186
1/26	15.7	1270	1097	1977	2201
1/26	17.7	1479	1253	2167	2363
1/26	18.7	1599	1307	2218	2451
1/28	5.2	258	313	641	860
1/28	10.0	572	655	1301	1559
1/28	14.8	871	1015	1717	2080
1/28	18.0	1304	1268	1715	2373
1/29	19.6	1587	1307	2797	2092
1/30	19.6	1397	1286	2656	2151
1/30	19.6	1367	1285	2577	2152
1/30	19.6	1206	1277	2487	2182
2/2	10.1	536	657	1456	1660
2/2	15.1	736	1013	2023	2196

FIGURE 2-3 FUEL TEMPERATURE VS POWER (T/C #1)

FIGURE 2-4 FUEL TEMPERATURE VS. POWER (T/C #2)

FIGURE 2-5 FUEL TEMPERATURE VS. POWER (T/C #4)

FIGURE 2-6 FUEL TEMPERATURE VS. POWER (T/C #18)

FIGURE 2-7 FUEL TEMPERATURE VS. POWER (T/C #20)

irradiation, or both. In any event, the practical upper limit for these T/C's appears to be $\sim 3000^{\circ}\text{F}$.

2.2 COOLANT TEMPERATURE MEASUREMENTS

Each instrumented fuel assembly (IFA) has in-channel chromel-alumel thermocouples to measure coolant temperature above and below the fuel zone of the rod assembly. The single inlet temperature thermocouple and two outlet temperature thermocouples are located on the tightener rod located in the center of the IFA. Their temperature sensitive hot junctions extend into the flow path of the channel coolant and thus measure directly the temperature of the sodium.

For the initial rise to a reactor power of 2 MW in the first week of July, 1970 all coolant thermocouples were operating satisfactorily. Within the next few weeks the inlet thermocouple performance began to deteriorate however, and the temperatures indicated by the IFA inlet thermocouples approached those indicated by the IFA (and vessel) outlet thermocouples. The outlet thermocouples have continued to agree with the vessel outlet coolant thermocouples, and to record consistent and reproducible data throughout the experimental program, however and have shown none of the problems demonstrated by the inlet thermocouples. In Figure 2-8 the continuing lack of valid inlet thermocouple data is illustrated. The peripheral IFA inlet thermocouple closely follows the outlet thermocouple response during the later periods of operation with a consequent near zero indicated temperature rise across the core. The actual coolant temperature rise across the core ranged between $\sim 10^{\circ}\text{F}$ and $\sim 120^{\circ}\text{F}$ as the power varied between 2 and 17 MW (Table 3-9). The central IFA inlet thermocouple has likewise drifted toward the outlet thermocouple response, but not to the same degree as the peripheral inlet coolant temperature sensor.

The IFA outlet coolant temperature data are shown in Figures 2-9 and 2-10 as percent deviation from the vessel coolant outlet temperature. The actual vessel coolant outlet temperatures are tabulated in Table 3-9. The relative agreement between the IFA outlet coolant temperatures and the vessel outlet temperatures is a result of the matching⁽⁷⁾ of channel flow orifice size with the radial power distribution.

FIGURE 2-9 COMPARISON OF CENTRAL IFA AND VESSEL COOLANT OUTLET TEMPERATURES

FIGURE 2-10 COMPARISON OF PERIPHERAL IFA AND VESSEL COOLANT OUTLET TEMPERATURES

SECTION 3

STATIC TEST RESULTS3.0 INTRODUCTION

The static tests at power were performed to determine the reactivity effects associated with changes between equilibrium power, core coolant temperature, and coolant flow conditions. These tests were used in conjunction with the oscillator tests (Section 5) to determine the Doppler coefficient of reactivity. The experimental data demonstrated, as expected⁽¹⁾, that reactivity changes are primarily a result of changes in power level and average core coolant temperature, and that reactivity effects associated with changes in other parameters such as core coolant inlet temperature, and reflector temperature are small. Since there are only two primary contributors to reactivity changes, the effects of the two parameters (power and average core coolant temperature) were separated by observing the reactivity changes associated with changes in each parameter while the other was held constant.

The experiments that were performed to illustrate the small reactivity effect of changes in the reflector temperature are described in Appendix III. The other static experiments are described below. The reactivity effects associated with a change in power while the average core coolant temperature is maintained constant are particularly relevant to determination of the Doppler, because for these experiments the reactivity changes are composed of the following two effects:^(1,2) 1) the reactivity change due to axial expansion of the fuel and fuel-clad as they are heated, and 2) the reactivity change due to Doppler broadening of the nuclear cross sections as the fuel is heated. Because SEFOR has segmented fuel rods and dished fuel pellets, the former effect is small⁽²⁾, and the dominant component is the Doppler effect.

3.1 POWER REACTIVITY MEASUREMENTS TO 20 MW

The power levels, average coolant temperatures, and reflector positions measured at average coolant temperatures of ~760°F and power levels up to

20 MW during the performance of the static tests in the initial power ascension phase of the SEFOR experimental program⁽¹⁾ are listed in Tables 3-1 and 3-2. Also shown in these tables are the reactivity effects due to power changes at a constant average coolant temperature of 760°F. These tabulated reactivity values have been corrected for the variations in average sodium temperature using measured temperature reactivity coefficients and an approximation to the theoretical dependence of the average core coolant temperature reactivity coefficient on reactor power. At 760°F coolant temperature, the correction can be written as $-0.35 - .19 (1220)/(1220+65P)$ cents/°F, where the power level, P, is in units of MW. The first term in this expression is the expected non-Doppler contribution while the latter term approximates the Doppler effect observed (and calculated) at power levels up to 20 MW. Some of the values in Tables 3-1 and 3-2 are averages of several measurements. The individual measurements from which these averages were obtained are listed in Tables 3-3 through 3-8. The thermal power levels and average coolant temperatures were calculated using the actual flow and temperature data in Table 3-9. The temperature dependence of the sodium heat capacity and density that were used in the calculations are illustrated in Figures 3-1 and 3-2. These curves are contained in the G.E. BRDO "SEFOR Standard Data Book" that indicates references 3 through 7 for the source material in the curves.

A comparison of the reactivity at zero power in early July (Table 3-3) with that in early August (Table 3-4) indicates a loss in reactivity during this period of $\sim 5.5 \pm 1.5$ cents. The calculated loss due to burnup (2180 MW hr) during this interval is 3.5 cents and the estimated loss due to Pu-241 decay contributes an additional ~ 1 cent. A change in core loading on 8/21/70 (see Appendix I) caused a change in the zero power reference critical point. This change is reflected in the values in Table 3-5. The measured change in reactivity between zero power conditions in late August 1970 (Table 3-5) and late January 1971 (Table 3-6) is $\sim 21 \pm 2$ cents. The calculated change due to burnup in this interval (about 550 MW-days) is 20¢, while the calculated change due to Pu-241 decay contributes an additional 4 cents for a total calculated change of 24¢. The calculated and measured values thus appear to be in acceptable agreement.

The data in Tables 3-1 and 3-2 (also see Table 3-11) indicate that the integral power reactivity effect may be decreasing slightly with time. This is the behavior which would be expected were the fuel temperatures to decrease slightly as the new fuel pellets begin to crack and expand to fill the fuel-cladding gap, and as the hotter pellets begin to form central voids as a result of operation at higher power levels. Such behavior would cause a slight change in the power-fuel temperature relation, and thus a small change in power-reactivity effect, even though the fuel temperature-reactivity relation remained unchanged.

POWER REACTIVITY DATA TO 17 MW

Date (1970)	Reflector #3		Reflector #8		Average Core*	Thermal	Neutron	Reactivity Change*
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)	Coolant Temperature (°F)	Power (MW)	Instrumentation (MW)	at 760°F Average Coolant Temperature (¢)
6/30-7/8	0	0	-	51.44	760.0†	0	-	0
7/2	0	0	37.61	50.42	744.0	0.4	0.5	-7.6
7/2	0	0	41.04	56.95	745.5	0.8	0.9	-13.3
7/2	0	0	48.16	70.60	763.2	1.0	1.1	-17.5
7/2	17.0	16.32	40.00	54.96	763.2	1.0	1.1	-18.2
7/3	16.76	16.00	47.00	68.42	759.1	2.0	2.0	-33.4
7/9-7/24	-	59.45†	47.00†	68.42†	760.0†	5.1†	5.1†	-76.4
8/6-8/16	-	-	-	56.75†	760.0†	0	-	0
8/6	18.79	18.81	47.00	68.40	759.0	2.2	2.0	-31.0
8/7	43.70	62.58	47.00	68.40	760.1	5.2	5.1	-74.2
8/14	42.32	59.99	47.01	68.42	758.1	4.9	5.0	-72.6
8/14	50.83	75.95	47.01	68.42	763.7	6.0	6.1	-85.8
8/14	57.43	87.58	47.01	68.42	765.2	7.0	7.2	-96.7
8/14	62.11	95.52	47.01	68.42	760.6	8.0	8.1	-106.8
8/14	70.00	107.75	47.07	68.53	760.2	9.1	9.3	-119.5
8/14-8/17	70.00†	107.75†	-	77.14	760.0†	10.0†	10.2†	-128.2
8/23-8/30	0	0	-	21.47†	760.0†	0	-	0
8/23	40.00	55.62	30.82	37.97	759.7	5.1	5.2	-72.3
8/29	40.00	55.62	58.63	89.64	758.3	10.1	10.2	-124.6
8/29	40.00	55.62	64.00	98.51	759.6	11.2	11.1	-132.8
8/29	40.20	56.01	70.00	107.54	758.0	12.5	12.4	-143.0
8/29	43.35	61.92	70.00	107.54	757.4	13.2	13.2	-148.9
8/29	46.89	68.59	70.00	107.54	757.5	14.0	14.0	-155.8
8/29	53.48	80.73	70.00	107.54	759.4	15.5	15.3	-167.1
8/29	51.42	77.12	70.00	107.54	759.5	14.8	14.8	-163.4
8/30	50.19	74.77	70.00	107.54	756.2	14.8	14.9	-162.7
8/30	51.19	76.61	70.00	107.54	758.9	15.1	15.2	-166.1
9/4	57.50	87.70	40.00	54.96	762.2	9.9	10.0	-120.1
9/5	58.39	89.23	40.00	54.96	760.4	10.1	10.1	-122.6
9/5	50.57	75.47	70.00	107.54	756.1	15.0	15.1	-163.3
9/5	50.81	75.91	70.00	107.54	756.2	15.0	15.1	-163.7
9/5	61.00	93.69	70.00	107.54	759.1	17.2	17.4	-180.1
9/6	60.70	93.20	70.00	107.54	757.7	17.2	17.3	-180.3

*Reactivity-temperature corrections made using a reactivity coefficient of $[-0.35 - \frac{0.19(1220)}{1220+65P}]¢/°F$ at power level P in MW. Estimated deviation in coolant temperatures is $\pm 0.25° F$.

The estimated standard deviation in the relative reactivity is $\pm 1.6¢$ or $\pm 3\%$ of the reactivity, whichever is larger. See Section 3.2.2 for deviations in power.

† Average values obtained from Tables 3-3 through 3-8.

TABLE 3-2

POWER REACTIVITY DATA TO 20 MW

<u>Date</u> (1971)	<u>Reflector #3</u>		<u>Reflector #8</u>		<u>Average Core*</u> <u>Coolant</u> <u>Temperature</u> (°F)	<u>Thermal</u> <u>Power</u> (MW)	<u>Reactivity</u> <u>Change*</u> <u>at 760°F</u> <u>Coolant</u> <u>Temperature</u> (°C)
	<u>Position</u> (cm)	<u>Worth</u> (¢)	<u>Position</u> (cm)	<u>Worth</u> (¢)			
1/25-2/2		42.40 [†]	0	0	760.0 [†]	0.0	0.0
1/25	40.00	55.63	38.79	52.65	759.3	5.1	66.2
1/26	40.00	55.63	67.94	104.56	760.4	10.1	117.6
1/26	59.84	91.71	70.00	107.54	761.8	14.7	156.0
1/26	62.17	95.62	70.00	107.54	755.6	15.6	162.8
1/26	64.41	99.33	70.00	107.54	760.5	15.7	164.2
1/26	73.20	111.78	70.00	107.54	756.7	17.7	178.4
1/26	79.98	119.41	70.00	107.54	759.8	18.7	184.6
1/28	40.00	55.63	39.38	53.77	758.0	5.2	68.0
1/28	40.00	55.63	70.00	107.54	764.4	10.0	118.7
1/28	60.83	93.38	70.00	107.54	761.0	14.8	158.1
1/28	74.18	112.95	70.00	107.54	753.2	18.0	181.2
1/29	95.07	129.18	66.70	102.71	754.9	19.8	191.7
1/29	95.07	129.18	67.00	103.16	750.8	19.6	194.0
1/30	95.07	129.18	67.64	104.11	752.1	19.6	194.4
1/30	95.07	129.18	66.96	103.10	751.2	19.6	193.8
1/30	95.07	129.18	67.20	103.46	751.9	19.6	193.8
2/2	40.00	55.63	65.20	100.40	741.5	10.1	122.3
2/2	62.62	96.36	70.00	107.54	756.5	15.1	163.1

*Reactivity temperature corrections made using a reactivity coefficient of

$\left[-0.35 - \frac{0.19(1220)}{1220+65P}\right] \text{ ¢/°F}$ at power level P (MW). Estimated deviation in coolant temperature is $\pm 0.25^\circ\text{F}$.

The estimated standard deviation in the relative reactivity is $\pm 1.6\text{¢}$ or $\pm 3\%$ of the reactivity, whichever is larger. See Section 3.2.2 for deviations in power.

[†]Average values obtained from Table 3-3.

TABLE 3-3

ZERO POWER CRITICAL POINTS (6/30/70-7/8/70)

<u>Date</u>	<u>Reflector #3</u>		<u>Reflector #8</u>		Reactor inlet [†] temperature (°F)	Relative Reactivity* at 760°F (¢)
	<u>Position</u> (cm)	<u>Worth</u> (¢)	<u>Position</u> (cm)	<u>Worth</u> (¢)		
6/30/70	0	0	35.74	46.92	751	51.76
7/1/70	0	0	37.91	50.97	760	50.97
7/8/70	0	0	29.70	35.99	731	<u>51.58</u>
Average =						51.44

*Reactivity temperature corrections were made with a previously measured⁽⁸⁾ coefficient of $-0.54\text{¢}/^{\circ}\text{F}$.
The estimated uncertainty in reactivity is $\pm 1.6\text{¢}$.

[†]The recorded panel temperature readings have been increased by one degree to account for an observed offset from the data acquisition system readings used in the other tables. The estimated uncertainty in temperature is $\pm 2.5^{\circ}\text{F}$.

TABLE 3-4

LOW POWER (0.06 MW) CRITICAL POINTS (8/6/70-8/16/70)

<u>Date</u>	<u>Reflector #3</u>		<u>Reflector #8</u>		<u>Reactor Coolant† Temperature</u> (°F)	<u>Relative Reactivity* at 760°F and Zero Power</u> (¢)
	<u>Position</u> (cm)	<u>Worth</u> (¢)	<u>Position</u> (cm)	<u>Worth</u> (¢)		
8/6/70	0	0	33.97	43.66	735	56.02
8/14/70	0	0	41.01	56.90	760	55.83
8/16/70	0	0	39.56	54.11	750	<u>58.42</u>
					Average	= 56.75

*Reactivity temperature corrections were made with a coefficient⁽⁸⁾ of $-0.54\text{¢}/^{\circ}\text{F}$ and a reactivity correction of 1.08 cents to the zero power point was made with a power reactivity coefficient at low power of $-18\text{¢}/\text{MW}$. The estimated uncertainty in the reactivity is $\pm 1.6\text{¢}$.

†The estimated uncertainty in temperature is $\pm 2.5^{\circ}\text{F}$.

TABLE 3-5

LOW POWER (0.06 MW) CRITICAL POINTS (8/23/70-8/30/70)

<u>Date</u>	<u>Reflector #3</u>		<u>Reflector #8</u>		<u>Reactor Coolant† Temperature</u>	<u>Relative Reactivity* at 760°F and Zero Power</u>
	<u>Position</u>	<u>Worth</u>	<u>Position</u>	<u>Worth</u>		
	(cm)	(¢)	(cm)	(¢)	(°F)	(¢)
8/23/70	0	0	18.56	18.52	752.4	21.53
8/23/70	0	0	18.23	18.06	751.7	21.46
8/25/70	0	0	21.22	22.38	761	20.77
8/30/70	0	0	20.30	21.03	756	<u>22.10</u>
					Average =	21.47

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Reactivity temperature corrections were made with a coefficient of $-0.54\text{¢}/^\circ\text{F}$ and a reactivity correction of 1.08 cents to the zero power point was made with a power reactivity coefficient at low power of $-18\text{¢}/\text{MW}$. The estimated uncertainty is $\pm 1.6\text{¢}$.

The estimated uncertainty in temperature is $\pm 2.5^\circ\text{F}$.

TABLE 3-6

LOW POWER (.06 MW) CRITICAL POINTS (1/25/71-2/2/71)

<u>Date</u>	<u>Reflector #3</u>		<u>Reactor Coolant Temperature</u> (°F)	<u>Relative Reactivity*</u> at 760°F and Zero Power (¢)
	<u>Position</u> (cm)	<u>Worth</u> (¢)		
1/25/71	30.57	38.11	750	42.43
1/27/71	30.43	37.87	748	43.27
2/2/71	8.52	6.40	693	<u>41.50</u>
Average				= 42.40

*Reactivity temperature corrections were made with a coefficient of $-0.54\text{¢}/^{\circ}\text{F}$, and a reactivity correction of 1.08 cents to the zero power point was made with a power reactivity coefficient at low power of $-18\text{¢}/\text{MW}$. The estimated standard deviation in the relative reactivity is $\pm 1.6\text{¢}$. The estimated deviation in temperature is $\pm 2.5^{\circ}\text{F}$.

TABLE 3-7

5 MW POWER REACTIVITY DATA (7/9/70-7/24/70)

Date (1970)	<u>Reflector #3</u>		<u>Reflector #8</u>		Average Coolant* Temperature (°F)	Thermal Power (MW)	Neutron Instrumentation (MW)	Reactivity Change* at a 760°F Average Coolant Temperature (¢)
	<u>Position (cm)</u>	<u>Worth (¢)</u>	<u>Position (cm)</u>	<u>Worth (¢)</u>				
6/30-7/8	0	0	-	51.44†	760.0†	0		0
7/9	42.20	59.76	47.00	68.40	760.8	5.0	5.1	-76.3
7/9	42.20	59.76	47.00	68.40	760.4	5.1	5.1	-76.5
7/10	42.94	61.15	47.00	68.40	760.8	5.2	5.1	-77.7
7/10	42.17	59.71	47.00	68.40	759.9	5.1	5.1	-76.7
7/10	42.22	59.80	47.00	68.40	761.7	5.2	5.1	-76.0
7/11	41.00	57.52	47.00	68.40	759.8	5.0	4.9	-74.4
7/23	41.75	58.91	47.00	68.40	758.7	5.0	5.1	-76.4
7/24	42.08	59.54	47.00	68.40	758.5	<u>5.2</u>	<u>4.9</u>	<u>-77.2</u>
						5.1	5.1	-76.4

*Temperature-reactivity corrections made using a reactivity coefficient of $-0.50\text{¢}/^\circ\text{F}$. The estimated standard deviation in these reactivities is $\pm 1.6\text{¢}$. The estimated deviation in coolant temperature is $\pm 0.25^\circ\text{F}$.

†Average values obtained from Table 3-3.

TABLE 3-8

10 MW POWER REACTIVITY DATA (8/14/70-8/17/70)

Date (1970)	<u>Reflector #3</u>		<u>Reflector #8</u>		Average Coolant* Temperature (°F)	Thermal Power (MW)	Neutron Instrumentation (MW)	Reactivity Change* at a 760°F Average Coolant
	<u>Position</u> (cm)	<u>Worth</u> (¢)	<u>Position</u> (cm)	<u>Worth</u> (¢)				<u>Temperature</u> (¢)
8/6-8/16	-	-	-	56.75†	760.0†	0	-	-
8/14	70.00	107.75	52.68	79.07	760.8	10.1	10.3	-129.7
8/15	70.00	107.75	51.89	77.61	759.9	10.1	10.3	-128.6
8/17	70.00	107.75	50.47	74.95	759.7	<u>9.9</u>	<u>10.1</u>	<u>-126.1</u>
						10.0	10.2	-128.2

*Temperature-reactivity corrections made using a reactivity coefficient of $-0.47\text{¢}/^{\circ}\text{F}$. The estimated standard deviation in reactivity is $\pm 1.6\text{¢}$. The estimated deviation in coolant temperature is $\pm 0.25^{\circ}\text{F}$.

†Average values obtained from Table 3-4.

TABLE 3-9
HEAT BALANCE DATA

Date (1970)	Main Primary System		Flow (gpm)	Auxiliary Primary System		Flow (gpm)	Thermal Power (MW)	Average Coolant Temperature (°F)
	Inlet* Temperature (°F)	Outlet* Temperature (°F)		Inlet* Temperature (°F)	Outlet* Temperature (°F)			
7/2	741.2	746.2	1987	747.2	748.4	185	0.4	744.0
7/2	740.5	750.1	1995	744.7	752.8	185	0.8	745.5
7/2	757.2	769.0	1998	758.7	771.7	185	1.0	763.2
7/3	747.8	769.8	2189	755.1	772.4	182	2.0	759.1
7/9	734.1	787.1	2326	743.3	786.3	180	5.0	760.8
7/9	733.7	786.4	2354	743.2	786.0	179	5.1	760.4
7/10	733.8	787.4	2347	740.7	786.0	181	5.2	760.8
7/10	732.8	786.6	2336	738.9	784.8	180	5.1	759.9
7/10	734.2	788.8	2342	741.4	786.0	173	5.2	761.7
7/11	744.0	775.5	3991	749.4	775.1	164	5.0	759.8
7/23	719.9	797.3	1512	724.9	794.3	182	5.0	758.7
7/24	745.3	771.6	5000	744.3	773.1	151	5.2	758.5
7/27	579.5	628.7	2480	578.9	625.0	153	5.2	604.0
7/27	579.1	628.3	2594	578.4	624.2	150	5.4	603.6
7/27	475.8	525.5	2516	479.4	519.2	152	5.4	500.6
7/28	376.8	426.8	2587	383.7	421.1	150	5.8	401.8
8/6	747.6	770.2	2412	751.0	769.6	151	2.2	759.0
8/7	734.2	786.3	2427	730.9	782.9	149	5.2	760.1
8/14	734.1	783.0	2449	727.3	777.4	171	4.9	758.1
8/14	734.0	794.1	2455	729.0	787.1	148	6.0	763.7
8/14	730.1	800.9	2458	726.2	793.2	145	7.0	765.2
8/14	720.8	801.0	2464	720.3	792.3	146	8.0	760.6
8/14	714.5	806.4	2443	715.3	796.7	146	9.1	760.2
8/14	710.0	812.2	2456	711.8	800.3	145	10.1	760.8
8/15	734/5	785.6	5000	732.7	779.5	147	10.1	759.9
8/17	699.7	820.7	1996	697.6	808.2	147	9.9	759.7
8/18	504.1	615.7	2050	503.5	602.8	147	10.0	559.4
8/23	735.3	784.0	2483	736.0	784.6	237	5.1	759.7
8/29	709.8	807.1	2505	711.7	802.2	210	10.1	758.3
8/29	723.0	796.9	3715	713.6	792.7	209	11.2	759.6
8/29	716.7	799.7	3703	714.5	794.6	212	12.5	758.0
8/29	713.7	801.3	3710	714.0	796.1	212	13.2	757.4
8/29	710.7	804.3	3703	714.6	798.8	211	14.0	757.5

TABLE 3-9 (Continued)

HEAT BALANCE DATA

Date (1970)	Main Primary System		Flow (gpm)	Auxiliary Primary System		Flow (gpm)	Thermal Power (MW)	Average Coolant Temperature (°F)
	Inlet* Temperature (°F)	Outlet* Temperature (°F)		Inlet* Temperature (°F)	Outlet* Temperature (°F)			
8/29	708.4	810.7	3748	709.1	803.6	210	15.5	759.4
8/29	710.1	809.2	3703	710.1	802.5	209	14.8	759.5
8/30	695.4	817.2	2981	699.3	808.9	208	14.8	756.2
8/30	697.3	820.7	2986	702.0	812.3	217	15.1	758.9
9/4	715.5	809.1	2534	717.9	804.5	248	9.9	762.2
9/5	735.4	785.6	5000	733.6	784.1	230	10.1	760.4
9/5	695.3	817.1	3008	699.6	808.5	213	15.0	756.1
9/5	706.6	806.1	3737	707.8	799.3	208	15.0	756.2
9/5	713.9	804.5	4748	716.7	798.0	218	17.2	759.1
9/6	712.5	802.9	4760	717.0	797.3	220	17.2	757.7

*To account for observed differences between inlet and outlet temperature readings at zero power the tabulated temperatures have been adjusted from the actual recorded value as follows: between 7/2/70 and 7/11/70 the main inlet temperature was decreased 2°F and the auxiliary inlet temperature was decreased 1°F, electronic amplifiers were adjusted on 7/23; between 7/23 and 8/7 the auxiliary outlet temperature was increased 1°F while the main outlet temperature was increased 2°F between 7/27 and 8/7; between 8/14 and 9/6 the main outlet temperature was increased 0.5°F; the auxiliary outlet was decreased 2.1°F between 8/14 and 8/18 and was increased 1.3°F between 8/23 and 9/6.

TABLE 3-9 (Continued)

HEAT BALANCE DATA

<u>Date</u> (1971)	<u>Main Primary System</u>			<u>Auxiliary Primary System</u>			<u>Thermal Power</u> (MW)	<u>Ave. Coolant Temperature</u> (°F)
	<u>Inlet Temperature</u> (°F)	<u>Outlet⁺ Temperature</u> (°F)	<u>Flow</u> (gpm)	<u>Inlet*</u> <u>Temperature</u> (°F)	<u>Outlet⁺ Temperature</u> (°F)	<u>Flow</u> (gpm)		
1/25	741.2	777.3	3519	745	773.7	240	5.1	759.3
1/26	726.1	795.6	3525	718	788.0	239	10.1	760.4
1/26	711.0	813.1	3539	713	802.2	239	14.7	761.8
1/26	702.2	809.8	3552	700	798.0	237	15.6	755.6
1/26	700.0	821.6	3163	704	809.0	239	15.7	760.5
1/26	703.0	811.1	4061	701	799.3	235	17.7	756.7
1/26	703.0	817.3	4049	704	804.1	236	18.7	759.8
1/28	742.0	775.0	3786	730	770.4	234	5.2	758.0
1/28	732.0	797.4	3742	728	790.0	236	10.0	764.4
3-14 1/28	712.9	809.6	3768	714	799.6	235	14.8	761.0
1/28	694.7	812.5	3760	693	799.8	235	18.0	753.2
1/29	705.5	804.8	5001	705	792.5	228	19.8	754.9
1/29	699.7	802.0	4787	707	791.7	229	19.6	750.8
1/30	701.0	803.6	4778	704	792.2	226	19.6	752.1
1/30	700.2	802.5	4784	703	791.2	226	19.6	751.2
1/30	701.1	803.3	4788	701	792.2	229	19.6	751.9
2/2	708.5	774.9	3753	709	767.1	236	10.1	741.5
2/2	707.4	806.2	3771	707	796.2	234	15.1	756.5

*Auxiliary inlet temperature readings taken from operations instrumentation.

⁺To account for observed differences between inlet and outlet coolant temperature readings at zero power, the actual recorded outlet coolant temperatures were increased by 1.2°F.

FIGURE 3-2 SODIUM DENSITY

3.2 UNCERTAINTIES IN STATIC REACTIVITY AND POWER MEASUREMENTS

3.2.1 Deviations in Reactivity

Different measurements of the same critical configuration (the system conditions for which the reactor is exactly critical) of the reactor show small variations as a result of small variations in temperatures, power, instrumentation, core-reflector configurations, etc. This variation is demonstrated by the 5 MW data from Table 3-7 which has been rearranged in a more convenient form in Table 3-10. In this table the relative reactivity at a constant 760°F coolant temperature and a constant power level is tabulated for a number of measurements having the same nominal power and average coolant temperature conditions.

In one case the estimated standard deviation in reactivity is calculated using the power levels indicated by the thermal heat balances as a basis, while in the other, the power levels indicated by the neutron instrumentation are used. As the table indicates, the choice of power level indicator does not appear to have a significant effect on the estimated standard deviation in reactivity.

Based on the above data, the estimated standard deviation in a single measurement of a reactivity change (at power) that is calculated from the difference between two measurements of the critical point is $1.1\sqrt{2}$ cents, or 1.6 cents. This deviation is probably reasonable for reactivity changes which are of the order of 30 cents or less. For larger changes the reflector configurations change considerably, and the reflector interaction effects noted in reference 8 may increase the uncertainties. Under the experimental conditions employed here (the coarse reflectors adjacent to fine reflector are always completely raised) the maximum previously⁽⁸⁾ observed interaction effect was an apparent change of ~4% in a total reflector worth of ~1.3\$. Since the nominal interaction effect would be expected to be less than the maximum, the estimated standard deviation for reactivity measurement at power is taken as $\pm 1.6\text{¢}$ or $\pm 3\%$ of the reactivity change, whichever is larger.

3.2.2 Deviations in Power

The reactor power data that are tabulated in Table 3-10 can be used

TABLE 3-10

5 MW CRITICAL CHECKS

Measurement Number	Date (1970)	Reflector #3 Relative Worth (cents)	Average Coolant Temperature (°F)	$\frac{u_1}{\text{Thermal Power}}$ (MW)	$\frac{v_1}{\text{Neutron Instru-mentation}}$ (MW)	$\frac{x_1^*}{\text{Relative Reactivity at 760°F Coolant and 5.10 MW using thermal power values}}$ (cents)	$\frac{y_1^*}{\text{Relative Reactivity at 760°F coolant and 5.06 MW using neutron instru-mentation}}$ (cents)
1	7/9	59.76	760.8	5.03	5.13	60.20	58.52
2	7/9	59.76	760.4	5.06	5.12	60.04	58.84
3	7/10	61.15	760.8	5.15	5.12	60.15	60.03
4	7/10	59.71	759.9	5.14	5.12	59.28	59.04
5	7/10	59.80	761.7	5.21	5.08	57.63	58.71
6	7/11	57.52	759.8	4.99	4.86	58.94	60.02
7	7/23	58.91	758.7	4.98	5.12	61.00	58.84
8	7/24	59.54	758.5	<u>5.22</u>	<u>4.92</u>	<u>58.85</u>	<u>61.97</u>
				$\bar{u} = 5.10$	$\bar{v} = 5.06$	$\bar{x} = 59.51$	$\bar{y} = 59.50$

Estimated standard deviation for $x = \left[\sum_i (x_i - \bar{x})^2 / 7 \right]^{\frac{1}{2}} = 1.05\text{c}$

Estimated standard deviation for $y = \left[\sum_i (y_i - \bar{y})^2 / 7 \right]^{\frac{1}{2}} = 1.15\text{c}$

Estimated standard deviation for $u = \left[\sum_i (u_i - \bar{u})^2 / 7 \right]^{\frac{1}{2}} = 0.095 \text{ MW}$

Estimated standard deviation for $v = \left[\sum_i (v_i - \bar{v})^2 / 7 \right]^{\frac{1}{2}} = 0.106 \text{ MW}$

*Temperature and power reactivity corrections made using a temperature coefficient of $-0.50\text{c}/^\circ\text{F}$ and a power coefficient of $-12.0\text{c}/\text{MW}$. Small changes in these coefficients do not significantly alter the estimated standard deviations.

to obtain a measure of the standard deviation in power. A conservative (i.e. large) estimate of the standard deviation in power due to statistical fluctuations can be calculated by assuming that the true power level in each of the 8 measurements in Table 3-10 is exactly the same. Actually the true power level is probably slightly different in each case, but since two inexact instruments (1-thermal heat balance, and 2-neutron instrumentation) are used, its true value cannot be known exactly, even though it is believed to be close to the measured values.

The deviations calculated using the above assumption are listed in Table 3-10 as 0.095 MW for the thermal heat balance values and 0.106 MW for the neutron instrumentation. Although the individual power values calculated from a heat balance appear to be rather randomly distributed about their mean, the neutron instrumentation values are clumped in two sets, one containing 6 points near 5.1 MW and another containing 2 points near 4.9 MW. The estimated standard deviations are essentially the same for both the heat balance and neutron instrumentation values however, and the estimated standard deviation in power due to statistical fluctuations at 5 MW will be taken as 0.1 MW or 2% of the mean value. At higher power levels the deviation will also be taken as 2% of the mean power since the percentage deviations in power will be essentially the same at all power levels if the percentage fluctuations in flow are the same, as they appear to be, at all flow rates.

In addition to the uncertainty in power due to statistical fluctuations in instrumentation etc. there is a possible bias because of uncertainties in the absolute calibration of coolant flow and temperatures, and because of uncertainties in coolant density and heat capacity. This possible bias will be treated as a random error, since its magnitude and direction are unknown. The estimated possible uncertainty due to this effect is $\pm 5\%$ of the mean power level.

For power levels > 1 MW the overall estimated standard deviation in power level, including fluctuations and possible biases, is presently taken as $\pm 5\%$ of the mean power, or ± 0.1 MW whichever is larger. Additional measurements may modify this preliminary estimate to some extent, but since this is not a primary contributor to the uncertainty in the Doppler effect (see Section 6) improvement of this uncertainty will not significantly alter the uncertainty in the Doppler effect.

3.3 PRELIMINARY MEASUREMENTS OF COOLANT INLET TEMPERATURE COEFFICIENT

Although all the static test points in Tables 3-1 and 3-2 were obtained at essentially the same average core coolant temperature and power level, the coolant inlet temperatures (flows) were not always the same (see Table 3-9). To determine the reactivity effect of a change in sodium inlet temperature while maintaining the power and average coolant temperature constant, two different flows were used (~ 1500 gpm on July 23 and 5000 gpm on July 24) at a power level of 5 MW, and again at 10 MW (~ 2500 gpm on August 14 and ~ 5000 gpm on August 15) as indicated in Table 3-9. As the corresponding reactivity data in Tables 3-7 and 3-8 indicate, any reactivity effect associated with this change is less than the estimated standard deviation in reactivity ($\pm 1.6\%$), and may be neglected.

3.4 MEASURED DOPPLER POWER REACTIVITY EFFECTS

The reactivity effects shown in Tables 3-1 and 3-2 are composed of two effects: the loss in reactivity due to the axial expansion of the fuel and clad as it is heated, and a loss in reactivity due to Doppler broadening of the nuclear cross sections as the fuel temperature increases. SEFOR was designed⁽²⁾ with segmented fuel rods and dished fuel pellets to reduce the former effect however, and the dominant component is the Doppler effect.

The experimental Doppler components of the power reactivity effects are listed in Table 3-11 along with total power reactivity effect and the corrections which were applied to the actual experimental data to account for the reactivity effects associated with small changes in core coolant temperature. The reactivity temperature corrections were made with measured temperature coefficients as discussed in Section 3-1. The Doppler component of the reactivity effect was obtained by correcting the total reactivity change at a constant coolant temperature for the fuel and fuel-clad axial expansion effects by using a constant reactivity coefficient of $-0.5\%/MW$ that was obtained from calculations⁽²⁾ based on normalizations to the SEFOR mockup⁽⁹⁾ in ZPR-III. It is important to note that the corrections to the data are small, and that $\sim 95\%$ of the total measured reactivity change is the Doppler effect.

TABLE 3-11

DOPPLER POWER REACTIVITY MEASUREMENTS

Date (1970)	Thermal† Power (MW)	Coolant Temperature Reactivity Correction (cents)	Reactivity Change at 760°F Average Coolant Temperature (cents)	Doppler Effect* (cents)
6/30-7/8	0.0	-	0.0	0.0
7/2	0.4	-8.6	-7.6	-7.4
7/2	0.8	-7.8	-13.3	-12.9
7/2	1.0	+1.7	-17.5	-17.0
7/2	1.0	+1.7	-18.2	-17.7
7/3	2.0	-0.5	-33.4	-32.4
7/9-7/24	5.1	-0.1	-76.4	-73.9
8/6-8/16	0.0	-	0.0	0.0
8/6	2.2	-0.5	-31.0	-29.9
8/7	5.2	0.0	-74.2	-71.6
8/14	4.9	-1.0	-72.6	-70.2
8/14	6.0	+1.9	-85.8	-82.8
8/14	7.0	+2.5	-96.7	-93.2
8/14	8.0	+0.3	-106.8	-102.8
8/14	9.1	+0.1	-119.5	-115.0
8/14-8/17	10.0	-0.1	-128.2	-123.2

TABLE 3-11 (Continued)

DOPPLER POWER REACTIVITY MEASUREMENTS

Date	Thermal† Power	Coolant Temperature Reactivity Correction	Reactivity Change at 760°F Average Coolant Temperature	Doppler Effect *
(1970)	(MW)	(cents)	(cents)	(cents)
8/23-8/30	0.0	-	0.0	0.0
8/23	5.1	-0.2	-72.3	-69.8
8/29	10.1	-0.8	-124.6	-119.6
8/29	11.2	-0.2	-132.8	-127.2
8/29	12.5	-1.0	-143.0	-136.8
8/29	13.2	-1.2	-148.9	-142.3
8/29	14.0	-1.2	-155.8	-148.8
8/29	15.5	-0.3	-167.1	-159.4
8/29	14.8	-0.2	-163.4	-156.0
8/30	14.8	-1.8	-162.7	-155.3
8/30	15.1	-0.5	-166.1	-158.6
8/23-8/30	0.0	-	0.0	0.0
9/4	9.9	+1.2	-120.1	-115.2
9/5	10.1	+0.2	-122.6	-117.6
9/5	15.0	-1.8	-163.3	-155.8
9/5	15.0	-1.8	-163.7	-156.2
9/5	17.2	-0.4	-180.1	-171.5
9/6	17.2	-1.1	-180.3	-171.7

TABLE 3-11 (Continued)

DOPPLER POWER REACTIVITY MEASUREMENTS

Date	Thermal† Power	Coolant Temperature Reactivity Correction	Reactivity Change at 760°F Average Coolant Temperature	Doppler Effect*
(1971)	(MW)	(cents)	(cents)	(cents)
1/25-2/2	0.0	-	0.0	0.0
1/25	5.1	-0.3	-66.2	-63.7
1/26	10.1	+0.2	-117.6	-112.6
1/26	14.7	+0.8	-156.0	-148.7
1/26	15.6	-2.0	-162.8	-155.0
1/26	15.7	-0.2	-164.2	-156.4
1/26	17.7	-1.5	-178.4	-169.6
1/26	18.7	-0.1	-184.6	-175.3
1/25-2/2	0.0	-	0.0	0.0
1/28	5.2	-1.0	-68.0	-65.4
1/28	10.0	+2.1	-118.7	-113.7
1/28	14.8	+0.5	-158.1	-150.7
1/28	18.0	-3.1	-181.2	-172.2
1/29	19.8	-2.2	-191.7	-181.8
1/29	19.6	-4.1	-194.0	-184.2
1/30	19.6	-3.5	-194.4	-184.6
1/30	19.6	-3.9	-193.8	-184.0
1/30	19.6	-3.6	-193.8	-184.0
1/25-2/2	0.0	-	0.0	0.0
2/2	10.1	-8.7	-122.3	-117.3
2/2	15.1	-1.6	-163.1	-155.6

*Obtained from the adjacent column by accounting for the calculated fuel-fuel clad axial expansion reactivity effect of -0.5¢/MW . The estimated standard deviation in the Doppler effect is $\pm 2\text{¢}$ or $\pm 4\%$ of the effect, whichever is larger.

†The estimated standard deviation in power is $\pm 0.1\text{ MW}$ or $\pm 5\%$ of the power, whichever is larger.

Thus, large percentage uncertainties in the corrections would cause only small uncertainties in the measured Doppler effect.

A preliminary estimate of the standard deviation in the measured Doppler effect is $\pm 2.0\%$ or $\pm 4\%$ of the measured effect, whichever is larger. This estimate accounts for the uncertainties in reactivity discussed in Section 3.2 and includes an uncertainty of $\sim 40\%$ in the calculated fuel, and fuel-clad axial expansion effect. The uncertainties in power are discussed in Section 3.2.

3.5 MEASURED TEMPERATURE REACTIVITY EFFECTS AT CONSTANT POWER

The reactivity effect due to a change in average coolant temperature while holding the power constant was measured at two different power levels during the power ascension phase of the experimental program. The measured results are tabulated in Table 3-12.

The results in Table 3-12 show that the power calculated from a thermal heat balance and the power indicated by the neutron instrumentation (the wide range monitors - WRM's) tended to diverge as the coolant temperature was decreased below $\sim 700^\circ\text{F}$. Part of this difference is attributable to the increase in the number of neutron mean free paths between the core and the detector because of the increase in sodium density as the temperature is lowered. Calculations indicate that the WRM readings should decrease $\sim 6.5\%$ at a constant thermal power due to an increase in sodium density of 6% as the temperature is lowered from 760°F to 400°F . The other contributor to the observed trend is the influence of reflector configuration on the neutron detection rate in the WRM's. This effect was noted ⁽⁸⁾ during the initial core loading, where the WRM count rates were observed to decrease by $\sim 40\%$ more than the counts at the core center, when all 10 reflectors were completely lowered. If the total fission rate had remained constant, it is expected that the effect would have been less than this (the estimated value is $\sim 28\%$ rather than 40%), since the ratio of total power to in-core detector count rate is influenced by the flux shape changes resulting from changes in reflector configuration. For the change in reflector configuration between the 5 MW condition at a 760°F coolant temperature and that at a 400°F coolant

TABLE 3-12

COOLANT TEMPERATURE REACTIVITY DATA AT CONSTANT POWER

Date (1970)	Reflector #3		Reflector #8		Thermal Power (MW)	Neutron Instrumentation (MW)	Average Coolant Temperature (°F)	Reactivity** Change at a constant Thermal Power (¢)
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)				
7/9-7/24	-	59.45	47.00*	68.40	5.1*	5.1*	760.0*	0
7/27	35.53	45.59	0	0	5.2	4.9	604.0	83.4
7/27	36.80	48.01	0	0	5.4	5.1	603.6	83.7
7/27	40.00*	53.90	48.00†	68.78	5.4	4.9	500.6	138.8
7/28	0†	0	51.52†	69.43	5.8	5.1	401.8	197.5
8/14-8/17	70.00*	107.75	-	77.14	10.0	10.2*	760.0*	0
8/18	0	0	53.77	81.06	10.0	9.5	559.4	103.6

* Average values obtained from Tables 3-7 and 3-8.

** Power Reactivity corrections were made using a reactivity coefficient of -12.9¢/MW at 5 MW.

† Reflector #10, which as a reactivity worth of 130¢, was completely lowered at the two lower temperatures, and was completely raised at the higher temperatures.

temperature the WRM count rates would be expected to decrease by $\sim(1.5/10) \sim 28\%$ due to reflector effects alone. (Note that reflector #10 was completely lowered from the raised position, and #3 was completely lowered from a mid position.)

3.6 POWER REACTIVITY COEFFICIENTS

Power reactivity coefficients were determined from fits of mathematical models to the power reactivity data in Table 3-2. With one model the measured reactivity changes were corrected for the calculated fuel and fuel clad axial expansion reactivity effect (-0.5¢/MW), and the adjusted reactivity data were fitted with a logarithmic expression of the form $K_a = C \ln (T + aP + bP^2)$, where K_a is the adjusted reactivity, P is the power in MW, and T is an initial temperature in $^{\circ}\text{R}$. This model approximates the expected Doppler behavior, but relies on approximations to calculated fuel temperatures. With the other model the reactivity was simply expressed as a polynomial in power.

With the logarithmic model the parameters a and b were selected so that the term $aP + bP^2$ approximated the calculated increase in average fuel temperature over the range between zero and twenty megawatts, while the parameter C was chosen so that the weighted sum of the residuals between the adjusted reactivity-measured power values, and those calculated according to the logarithmic expression was a minimum. The power reactivity coefficient was then determined from the derivative, $\frac{dK_a}{dP}$, of the fitted expression; plus the calculated axial fuel and fuel clad coefficient. The values of a and b that were used in the fits are 82.7°R/MW and $-0.89^{\circ}\text{R/MW}^2$ respectively, and the initial value of the fuel temperature, T , was 1220°R . The weights for the residuals at a given power level were normally unity, but were taken equal to the number of measurements at a power level if averaged values, such as the initial 5.1 MW point, were used.

For the polynomial fits, coefficients, a_j , were selected so that the weighted sum, S_J , of the residuals between the measured reactivity, K , power, P , values, and those calculated from an expression of the form

$$K = \sum_{j=1}^J a_j P^j$$

was a minimum. The data were fit with 2nd, 3rd, etc. order polynomials, and a minimum of the quantity $S_J/(N-J)$, where N is the number of data

points, was used as a figure of merit to determine the order, J, of the polynomial that gave the "best" fit.

The static test data was broken up into four sets, power reactivity coefficients were determined from each set, and then all the data was combined to produce a composite set of data from which reactivity coefficients were determined. The results of the logarithmic fits are tabulated in Table 3-13 and those from the polynomial fits in Table 3-14. The "best" polynomial fit of the power reactivity data did not always provide a reasonable power reactivity coefficient (ρ /MW) however as some of the higher order fits tended to follow the data too closely and to produce unwarranted inflections in the curve. In these cases (sets 2 and 4) another polynomial was used if it provided a more reasonable coefficient, and if the figure of merit for this polynomial was within^{*} $\sim 25\%$ of that for the "best" polynomial. A second order polynomial was used for data sets 1 and 2, a fourth order polynomial for set 3, and third order polynomials for set 4 and for the composite set.

The values in Tables 3-13 and 3-14 show good agreement between data sets and between the two types of fits at power levels of 5 and 10 MW. At the higher and lower power levels the polynomial fits demonstrate variations between data sets, and the polynomial and logarithmic fits tend to diverge when compared on a set to set basis. The coefficients determined from the composite set of data are in reasonable agreement regardless of the type of fit however. The coefficients in Tables 3-13 and 3-14 were used to generate an averaged set of coefficients that are tabulated in Table 3-15. The averaged coefficients were obtained by averaging the coefficients from the individual sets, and then averaging the result with the composite coefficients. The indicated deviations in Table 3-15 include the estimated deviations in power and in reactivity that are discussed in Section 3-2, and they include one half the spread between the averaged values and the individual values used in the final averaging, as well as one-half the maximum spread between the averaged values and a corresponding value from any of the individual sets. As the values of Table 3-15 indicate, this estimating procedure gives a deviation that ranges between a minimum of about 7% at 10 MW to a maximum of about 15% at 20 MW. These coefficients are compared with the oscillator results and with calculations in Section 6.

*Data set 2 was an exception and the figure of merit for the second order polynomial was a factor of 2 larger than the minimum.

Table 3-13

POWER COEFFICIENTS - LOGARITHMIC FITS

Power (MW)	Power Reactivity Coefficients (ρ /MW)				
	Set 1	Set 2	Set 3	Set 4	Composite
	7/2/70	8/6/70	8/23/70	1/25/71	
	to 7/24/70	to 8/17/70	to 9/6/70	to 2/2/71	
0	-18.6	-18.3	-18.0	-17.5	-17.8
2	-15.8	-15.6	-15.3	-14.8	-15.1
5	-12.8	-12.5	-12.4	-12.0	-12.2
10	-	- 9.2	- 9.1	- 8.8	- 8.9
15	-	-	- 6.9	- 6.7	- 6.8
17.2	-	-	-6.2	- 6.0	- 6.1
19	-	-	-	- 5.4	- 5.5
20	-	-	-	- 5.2	- 5.3

Table 3-14

POWER COEFFICIENTS - POLYNOMIAL FITS

Power (MW)	Power Reactivity Coefficients (¢/MW)				
	Set 1 7/2/70 to 7/24/70	Set 2 8/6/70 to 8/17/70	Set 3 8/23/70 to 9/6/70	Set 4 1/25/71 to 2/2/71	Composite
0	-18.0	-16.2	-17.7	-14.8	-16.4
2	-15.6	-14.8	-14.7	-13.4	-14.5
5	-12.1	-12.9	-11.6	-11.4	-12.0
10	-	- 9.6	- 9.1	- 9.0	- 8.8
15	-	-	- 7.8	- 7.4	- 6.7
17.2	-	-	- 7.1	- 7.0	- 6.1
19	-	-	-	- 6.8	- 5.8
20	-	-	-	- 6.8	- 5.6

Table 3-15

AVERAGED POWER REACTIVITY COEFFICIENTS

Power (MW)	Reactivity Coefficient (ρ /MW)
0	-17.3 $\pm$ 1.7
2	-14.9 $\pm$ 1.2
5	-12.1 $\pm$ 0.8
10	- 9.0 $\pm$ 0.6
15	- 7.0 $\pm$ 0.6
17.2	- 6.4 $\pm$ 0.6
19	- 5.9 $\pm$ 0.7
20	- 5.7 $\pm$ 0.8

SECTION 4

SEFOR ZERO POWER OSCILLATOR TESTS4.0 SUMMARY

Conventional oscillator tests were performed at a low (zero) enough power level that the power oscillations induced by the oscillating B_4C rod would produce negligible reactivity feedback. The zero power reactivity transfer function was then used in conjunction with the oscillator tests performed at higher power levels to determine the frequency dependent reactivity feedback (see Section 5).

A theoretical model for the inverse of the zero power reactivity transfer function was fit to the experimental zero power oscillator test data. The good agreement ⁽¹⁾ between prediction and experiment afforded the opportunity for this analysis. The primary purpose of the analysis was to obtain a "best" analytical model for use during the later determination of reactivity feedback effects from the oscillator tests at power. Such a model is desirable since it is applicable at any frequency, while the zero power experimental data can only be used at the frequencies where the data was obtained. A secondary purpose of the fitting was to obtain an estimate of the effective delayed neutron fraction β . In addition, an "experimentally determined" relationship (the inhour equation) between asymptotic period and reactivity was afforded since the zero power transfer function and the inhour equation involve the same characteristic parameters. The estimated value of β obtained from the analysis is 0.00327. This is in good agreement with the previously calculated value of 0.00315. A comparison of the inhour equation inferred from the zero power oscillator tests with the calculated relation is given in Appendix II.

4.1 DESCRIPTION OF EXPERIMENT

The zero power oscillator test was performed by oscillating a boron-carbide rod in the central dry well to produce sinusoidal oscillations in the reactivity and the neutron flux. The time dependent

TABLE 4-1

FREQUENCIES OF OSCILLATION

<u>DESIGNATION</u>	<u>RADIANS/SECOND</u>	<u>CYCLES/SECOND</u>
F2	1.56	0.25
F3	0.98	0.16
F4	0.61	0.097
F5	0.35	0.056
F6	0.22	0.035
S1	0.13	0.021
S2	0.078	0.0125
S3	0.049	0.0078
S4	0.031	0.0049
S5	0.018	0.0029
S6	0.011	0.00175

TABLE 4-2

ZERO POWER OSCILLATOR RECORDS

Set 1			Set 2			Set 3		
(Tape No. 55)			(Tape No. 26)			(Tape No. 53)		
Frequency	Rod Amplitude (inches)	File No.	Frequency	Rod Amplitude (inches)	File No.	Frequency	Rod Amplitude (inches)	File No.
F2	3.00	12	F2	3.9	13	F2	1.6	2
F2	3.96	13	F2	3.35	14	F3	1.6	3
F3	3.89	14	F3	3.35	15	F3	0.68	4
F4	3.27	15	F4	3.35	16	F4	0.69	5
F5	3.11	16	F4	2.3	17	F4	1.24	6
F6	2.50	17	F5	2.3	18	F5	1.24	7
S1	1.85	18	F6	2.3	19	F6	1.24	8
S2	1.58	19	F6	1.5	20	F6	0.70	9
S3	0.96	20	S1	1.56	21	S1	0.71	10
S4	0.74	21	S2	0.78	23	S2	0.70	11
S4	0.74	22	S3	0.78	24	S3	0.71	12
S5	0.46	23	S3	0.35	1*	S4	0.71	13
S6	0.32	24	S6	.34	27	S4	0.44	14
			S6	.36	25	S5	0.46	15
						S6	0.24	16

* From Tape No. 53

rod position, and the signals from two of the operational neutron monitors located below the vessel (and approximately 5 ft. below the core) were recorded on magnetic tape with the data acquisition system. The sampling rate was controlled by the oscillator rod position so that 32 nearly equally spaced samples were recorded in each cycle of oscillation.

During the experiment, the amplitudes of the power oscillations were always less than 20% of the mean value, and the mean was maintained at a low level (~ 1 KW) so that power dependent feedback effects were negligible.

The oscillator rod was positioned so that the lower end of the 26 inch long poison section was at an indicated mean height of 5.5 inches above the core midplane. This location was selected because oscillator rod worth measurements (see Appendix IV) had indicated a nearly linear dependence of reactivity on rod position in this region of the core. In order to limit the amplitude of the power oscillations, the rod was oscillated with an amplitude that ranged between ~ 4 inches or less at high frequencies and $\sim 1/4$ to $1/3$ inch at low frequencies. Eleven different frequencies of oscillation ranging between ~ 0.24 cps and 0.0018 cps were used, and three different sets of data covering the entire frequency range were obtained.

The nominal frequencies of oscillation are listed in Table 4-1 and the amplitude of the poison rod oscillations for each set of measurements are shown in Table 4.2. For reference purposes, the data tape and file * numbers are also included in Table 4.2. In addition to the measurements shown in the table, back-ground "noise" measurements at zero amplitude were obtained at each frequency for all three sets of data.

4.2 DESCRIPTION OF ANALYSIS

Most of the steps involved in the analysis have been described in detail in Reference 2, and will be only briefly discussed here. The equations and procedures used for the least squares analysis will be described in some detail however, as they differ from the expressions in the referenced document.

*Each file contains several consecutive cycles of measured data at a given frequency.

In order to determine the transfer function, the mean value of the flux signals, and the harmonic components of the flux and oscillator rod position signals were determined from the recorded experimental data. The amplitude of the rod oscillation was then converted to a reactivity oscillation by multiplying the displacement with a constant conversion factor of 2.51 cents/inch that had been determined from preliminary analysis of static worth versus rod position measurements (Appendix IV). Finally, the zero power reactivity transfer function was calculated at all frequencies by dividing the fundamental component of the flux signal with the product of the mean flux and the fundamental component of the reactivity oscillation. The resulting transfer functions were fit with the theoretical model.

In order to eliminate the effects of drift, particularly in the flux oscillations at low frequencies, the procedure described by Persson⁽³⁾ was used to determine the fundamental component of the signals. It was found that use of this method with at least six (or integer multiples of six) successive half cycles of data was generally sufficient to eliminate the effects of drift.

The contributions of the second and third harmonics to the flux signals was determined by a conventional Fourier analysis. These contributions were small and they were neglected in the analysis.

Analysis of the background data showed that the background noise is essentially zero, and that it does not contribute to the fundamental component of the signal.

4.3 FITTING OF THE DATA

The mathematical model for the inverse, $Z(i\omega)$, of the zero power transfer function can be written as follows:

$$Z(i\omega) = i\omega \left[\frac{\ell}{\beta} + \frac{1}{\beta} \sum_j f_j \sum_k \frac{\beta_{jk}}{\lambda_{jk} + i\omega} \right]$$

$$= i\omega \ell / \beta + \sum_j f_j T_j / \beta$$

where T_j is defined by this expression and where

i = the square root of minus one

w = the frequency in radians per second

ℓ = the prompt neutron lifetime

β = the effective delayed neutron fraction

f_j = the fraction of prompt neutrons produced by fissionable isotope j

β_{jk} = the effective delayed neutron fraction for isotope j and delay group k

λ_{jk} = the decay constant for isotope j and delay group k .

In SEFOR there are four fissionable isotopes that contribute to the delayed neutrons. These are U-238, Pu-239, Pu-240, and U-235. The contribution from Pu-241 is very small and was neglected. Most (~97%) of the delayed neutrons are produced by U-238 and Pu-239. The characteristics of the zero power transfer function are thus primarily determined by the relative delayed neutron contributions of these two isotopes. If the small contributions from Pu-240 and U-235 are treated as known quantities, the above expression, can be written as

$$Z = q_1 [T_1 + T_{34}] + q_2 [T_2 + T_{34}]$$

where $T_{34} = \frac{f_3}{\alpha} T_3 + \frac{f_4}{\alpha} T_4$

and where the insignificant contribution of $iw\ell/\beta$ in the frequency range of interest (0.01 to 1.5 radians per second) has been neglected.

In the above equation, the indices 1, 2, 3, 4 denote the isotopes U-238, Pu-239, Pu-240, and U-235 respectively; $\alpha = 1 - f_3 - f_4 = f_1 + f_2$; and $q_1 = f_1/\beta$ and $q_2 = f_2/\beta$. The above expression was fit to the experimental values of the inverse, $Z(iw_m)$, of the measured transfer function by minimizing the following sum S with respect to the parameters A_1 and A_2 .

$$S = \sum_m \left\{ \frac{\sigma_o^2}{\sigma_m^2} \left[X_m - A_1 R_{1m} - A_2 R_{2m} \right]^2 + \frac{\sigma_o^2}{\delta_m^2} \left[Y_m - A_1 I_{1m} - A_2 I_{2m} \right]^2 \right\}$$

In this sum X_m , R_{1m} , and R_{2m} are the real parts of Z , $T_1 + T_{34}$, and $T_2 + T_{34}$ respectively at frequency ω_m ; Y_m , I_{1m} , and I_{2m} are the corresponding imaginary components; σ_o is a normalization constant; and σ_m and δ_m are the estimated standard deviation in X_m and Y_m respectively.

The parameters A_1 and A_2 were determined from the fit. These parameters are the same as q_1 and q_2 of the previous expression except for a normalization constant $C = A_j/q_j$ which has been introduced to normalize the experimental data and to reduce the uncertainty introduced during the conversion of oscillator rod position to reactivity.

The equations for the two parameters are as follows:

$$A_j = \sum_{k=1}^2 Q_{jk} P_k \quad \text{for } j = 1, 2$$

where Q is the inverse of a T matrix whose elements are defined by

$$T_{jk} = \sum_m \frac{\sigma_o^2}{\sigma_m^2} R_{jm} R_{km} + \sum_m \frac{\sigma_o^2}{\delta_m^2} I_{jm} I_{km}$$

and P is a vector with elements defined by the following equation.

$$P_j = \sum_m \frac{\sigma_o^2}{\sigma_m^2} X_m R_{jm} + \sum_m \frac{\sigma_o^2}{\delta_m^2} Y_m I_{jm}$$

The estimated standard error $\bar{\sigma}_1$ and $\bar{\sigma}_2$ in the parameters A_1 and A_2 were also determined from the fit by using the following expression

$$\bar{\sigma}_j = \sigma \sqrt{Q_{jj}}$$

where $\sigma = \sqrt{\frac{S}{2M-2}}$

S is the sum defined above and M is the number of measurements in a given set.

The fractions f_1 and f_2 were determined from the values A_1 and A_2 according to the following expression for $j = 1, 2$.

$$f_j = \alpha A_j / (A_1 + A_2)$$

The effective delayed neutron fraction was determined from

$$\beta = \sum_j f_j \sum_k \beta_{jk}$$

and the normalizing factor C was determined from

$$C = (\beta/\alpha) (A_1 + A_2)$$

The estimated standard errors σ_β in β , σ_f in f_1 and f_2 (the error in f_1 is the same as in f_2), and σ_c in c were determined from the following expressions:

$$\sigma_f = \frac{\sigma}{A_1 + A_2} \sqrt{f_2^2 Q_{11} - 2 f_1 f_2 Q_{12} + f_1^2 Q_{22}}$$

$$\sigma_\beta = \sigma_f \left| \beta_1 - \beta_2 \right|$$

where β_1 and β_2 are defined below.

$$\sigma_c = \sigma \sqrt{Q_{11}E^2 - 2EGQ_{12} + G^2Q_{22}}$$

with E and G defined by

$$E = \alpha \beta_1 + (f_3\beta_3 + f_4\beta_4)/\alpha$$

$$G = E + \alpha (\beta_2 - \beta_1)$$

where the delayed neutron fraction β_j for each isotope ($j = 1, 2, 3, 4$) is defined by

$$\beta_j = \sum_k \beta_{jk}$$

The delayed neutron parameters given by Keepin⁽⁴⁾ were used in the analysis. In order to obtain the effective delayed neutron fractions, Keepin's values were modified by calculated effectiveness factors. The factors for the four isotopes were calculated under the assumption that the delayed neutron energy spectra were the same for all isotopes. The energy spectra for the first four groups was taken from Figure 4-5 of Reference 4, and the energy spectrum for the last two groups was assumed to be a composite of the other four spectra. The relative effectiveness factors (i.e. the ratio of the effective delayed neutron fraction to the actual delayed fraction) for groups 1 through 6 that were obtained from a perturbation calculation using the BISYN^(5,6) code are 0.8906, 0.9146, 0.9033, 0.9130, 0.9116 and 0.9116 respectively. The values $f_3 = 0.019$ and $f_2 = 0.008$ that were used in the analysis were obtained from calculated⁽⁷⁾ core average reaction rates.

4.4 RESULTS

The three sets of data in Table 4-2 were analyzed. Since the signals from two different flux detectors (denoted by A and B in Table 4-2) were included in each set, two "measured" power reactivity transfer functions at up to 15 frequency points were available from each of the three sets. These six separate groups of data were fitted in two ways. In one fitting, the standard deviations, σ_m and δ_m , which had been estimated from the "spread" in the fundamental components of the signals were used to obtain pointwise weight functions, σ_o^2/σ_m^2 and σ_o^2/δ_m^2 . A second fitting of the six groups was performed with a constant weight, since it was expected that the weights would be relatively constant, and the actual weights did not, in general, exhibit a great variance.

The results of the fits using the two types of weights are shown in Table 4-3. There seemed to be little difference in the two methods, and a weighted average of all values (the weights being proportional to the inverse square of the estimated standard errors) were used to obtain the values at the bottom of Table 4-3. The averaged value of β , 0.00327, is in good agreement with the calculated⁽⁷⁾ value of 0.00315. The average values for f_1 and f_2 were 0.118 and 0.855 respectively. The corresponding calculated values were 0.103 and 0.870. The average value of C was 0.9174. If the static rod worth calibration value of 2.51 cents/inch were also the correct calibration for this dynamic measurement, C would be unity. Since it is not, the dynamic worth of the rod is 9% higher than the static worth, and to correctly normalize the dynamic reactivity data a conversion factor of $2.51/(0.9174 \pm 0.037) = 2.736 \pm 0.110$ ¢/inch should be used.

It should be noted that the values of β , f_1 , and f_2 that are shown in Table 4-3 are those values that provide a best fit to the SEFOR oscillator data based on the calculated relative effectiveness factors, and the assumption that the model and the parameters in the model (the β 's and λ 's) are correct. The estimated standard errors which are shown therefore provide a measure of the goodness of fit, but may be misleading as to the actual uncertainty in the effective delayed neutron fraction and in the fraction of fissions produced by the two major fissionable isotopes.

TABLE 4-3

ZERO POWER OSCILLATOR FITTED PARAMETERS

Set No.	Flux Detector	Weights	Prompt Neutron Fraction for U-238	Prompt Neutron Fraction for Pu-239	Normalization Constant	Effective Delayed Neutron Fraction
			f_1	f_2	C	β
1	A	Pointwise	0.1224	0.8510	0.9342	0.00332
1	B	Pointwise	0.1255	0.8478	0.9386	0.00336
2	A	Pointwise	0.1212	0.8522	0.9210	0.00331
2	B	Pointwise	0.1258	0.8475	0.9172	0.00336
3	A	Pointwise	0.1128	0.8605	0.8977	0.00321
3	B	Pointwise	0.1136	0.8598	0.8943	0.00322
1	A	Constant	0.1231	0.8503	0.9367	0.00333
1	B	Constant	0.1225	0.8509	0.9340	0.00332
2	A	Constant	0.1213	0.8520	0.9216	0.00331
2	B	Constant	0.1142	0.8591	0.9177	0.00323
3	A	Constant	0.1016	0.8718	0.8942	0.00308
3	B	Constant	<u>0.1137</u>	<u>0.8597</u>	<u>0.8954</u>	<u>0.00322</u>
Weighted Average			0.118	0.855	0.9174	0.00327
			<u>+0.010*</u>	<u>+ 0.010*</u>	<u>+0.037*</u>	<u>+0.00010*</u>

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*Estimated standard errors obtained from the fit. These values do not reflect possible additional uncertainties introduced in the calculation of the effectiveness factors, nor the uncertainties in the actual isotopic β 's and λ 's.

The normalized experimental data are compared with the "best" calculated curves in Figures 4-1 through 4-8. The delayed neutron parameters which will be used in the analysis of the data at power are listed in Table 4-4, and the values of this transfer function and its inverse are tabulated at several frequencies in the range of interest in Table 4-5.

The values of the measured transfer functions are listed in Tables 4-6 through 4-8. The variations between measured data sets appears to be fairly random, and the average percentage fluctuations in the real and imaginary components of the transfer functions appears to be essentially independent of frequency. The estimated standard deviation in the real and imaginary components of the measured zero power reactivity transfer function is approximately $\pm 1.4\%$ at all frequencies.

FIGURE 4-1 IMAGINARY PART OF THE INVERSE OF THE ZERO POWER TRANSFER FUNCTION USING DETECTOR A

FIGURE 4-2 IMAGINARY PART OF THE INVERSE OF THE ZERO POWER TRANSFER FUNCTION USING DETECTOR B

FIGURE 4-3 REAL PART OF THE INVERSE OF THE ZERO POWER TRANSFER FUNCTION USING DETECTOR A

FIGURE 4-4 REAL PART OF THE INVERSE OF THE ZERO POWER TRANSFER FUNCTION USING DETECTOR B

FIGURE 4-5 AMPLITUDE OF THE ZERO POWER TRANSFER FUNCTION
USING DETECTOR A

FIGURE 4-6 AMPLITUDE OF THE ZERO POWER TRANSFER FUNCTION
USING DETECTOR B

FIGURE 4-7 PHASE OF THE ZERO POWER TRANSFER FUNCTION
USING DETECTOR A

FIGURE 4-8 PHASE OF THE ZERO POWER TRANSFER FUNCTION
USING DETECTOR B

TABLE 4-4

RECOMMENDED SEFOR DELAYED NEUTRON PARAMETERS

i	U-238		Pu-239		Pu-240		U-235	
	$F_1 = 0.118$		$F_2 = 0.855$		$F_3 = 0.019$		$F_4 = 0.008$	
	$\beta_i \times 10^5$	λ_i (sec)	$\beta_i \times 10^5$	λ_i (sec)	$\beta_i \times 10^5$	λ_i (sec)	$\beta_i \times 10^5$	λ_i (sec)
1	17.1	0.0132	6.95	0.0129	6.68	0.0129	21.7	0.0127
2	185.5	0.0321	52.22	0.0311	66.40	0.0313	124.8	0.0317
3	216.6	0.139	39.84	0.134	46.16	0.135	108.8	0.115
4	524.2	0.358	61.08	0.331	85.00	0.333	238.2	0.311
5	303.6	1.41	19.14	1.26	30.99	1.36	74.8	1.40
6	101.2	4.02	6.47	3.21	7.02	4.04	15.2	3.87
	<hr/>		<hr/>		<hr/>		<hr/>	
Total	1348.2		185.70		242.25		583.5	

TABLE 4-5

SEFOR ZERO POWER TRANSFER FUNCTION G_o

Frequency (radians/sec)	Real Part of the inverse of G_o (cents/%power)	Imaginary Part of the inverse of G_o (cents/%power)	Amplitude of G_o (percent power/ cents)	Phase of G_o (degrees)
0.00400	0.005760	0.04369	22.69	-82.49
0.00500	0.008794	0.05390	18.31	-80.73
0.00630	0.01348	0.06657	14.72	-78.56
0.00800	0.02061	0.08200	11.83	-75.89
0.0100	0.03008	0.09850	9.710	-73.02
0.0125	0.04296	0.1167	8.042	-69.79
0.0160	0.06191	0.1380	6.611	-65.84
0.0200	0.08364	0.1573	5.612	-62.00
0.0250	0.1095	0.1755	4.834	-58.04
0.0315	0.1397	0.1922	4.209	-54.00
0.0400	0.1728	0.2070	3.708	-50.14
0.0500	0.2045	0.2196	3.333	-47.04
0.0630	0.2379	0.2327	3.005	-44.37
0.0800	0.2742	0.2476	2.707	-42.08
0.100	0.3111	0.2626	2.456	-40.16
0.125	0.3522	0.2777	2.230	-38.26
0.160	0.4028	0.2929	2.008	-36.02
0.200	0.4531	0.3035	1.834	-33.81
0.250	0.5067	0.3094	1.684	-31.41
0.315	0.5640	0.3093	1.555	-28.74
0.400	0.6224	0.3019	1.446	-25.88
0.500	0.6735	0.2892	1.364	-23.24
0.630	0.7212	0.2721	1.297	-20.67
0.800	0.7650	0.2527	1.241	-18.28
1.00	0.8017	0.2342	1.197	-16.28
1.25	0.8350	0.2155	1.160	-14.47
1.60	0.8683	0.1945	1.124	-12.62
2.00	0.8949	0.1750	1.097	-11.06
2.50	0.9179	0.1555	1.074	- 9.614
3.15	0.9379	0.1357	1.055	- 8.234

TABLE 4-6

MEASURED ZERO POWER TRANSFER FUNCTION

Set 1

Frequency (radians/sec)	Amplitude of Zero Power Transfer Function (% power/c reactivity)		Phase of Zero Power Transfer Function (degrees)	
	<u>Detector A</u>	<u>Detector B</u>	<u>Detector A</u>	<u>Detector B</u>
0.0112	9.202	9.206	-71.26	-71.30
0.0178	6.048	6.022	-62.44	-62.46
0.0306	4.318	4.341	-53.30	-53.31
0.0306	4.324	4.339	-53.23	-53.74
0.0490	3.383	3.375	-46.19	-46.28
0.0780	2.714	2.726	-41.22	-41.11
0.1289	2.195	2.196	-36.93	-37.08
0.2231	1.737	1.748	-31.88	-31.82
0.3518	1.482	1.484	-26.92	-26.82
0.6071	1.285	1.288	-20.87	-20.83
0.9708	1.170	1.171	-16.44	-16.59
1.533	1.093	1.098	-13.02	-13.01
1.560	1.109	1.112	-13.15	-13.03

TABLE 4-7

MEASURED ZERO POWER TRANSFER FUNCTION

Set 2

Frequency (radians/sec)	Amplitude of Zero Power Transfer Function (% power/c reactivity)		Phase of Zero Power Transfer Function (degrees)	
	<u>Detector A</u>	<u>Detector B</u>	<u>Detector A</u>	<u>Detector B</u>
0.0112	9.075	9.065	-69.11	-69.17
0.0112	9.183	9.187	-69.93	-69.36
0.0488	3.415	3.401	-45.67	-47.78
0.0491	3.401	3.407	-46.47	-46.42
0.0779	2.814	2.796	-41.41	-41.29
0.1292	2.207	2.222	-37.25	-37.04
0.2225	1.779	1.787	-32.10	-32.18
0.2231	1.763	1.773	-32.17	-31.93
0.3521	1.510	1.517	-26.95	-27.01
0.6103	1.311	1.315	-20.70	-20.93
0.6091	1.292	1.300	-20.79	-20.99
0.9769	1.194	1.197	-16.42	-16.40
1.556	1.109	1.119	-12.82	-13.03
1.558	1.118	1.111	-12.96	-13.03

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TABLE 4-8

MEASURED ZERO POWER TRANSFER FUNCTION

Set 3

Frequency (radians/sec)	Amplitude of Zero Power Transfer Function (% power/¢ reactivity)		Phase of Zero Power Transfer Function (degrees)	
	<u>Detector A</u>	<u>Detector B</u>	<u>Detector A</u>	<u>Detector B</u>
0.0112	9.189	9.249	-69.02	-68.81
0.1783	-	6.285	-	-62.30
0.0308	4.387	4.365	-52.33	-53.16
0.0307	4.364	4.385	-53.41	-53.51
0.0490	3.333	3.398	-46.38	-46.31
0.0781	2.768	2.785	-41.35	-41.31
0.1291	2.248	2.265	-36.83	-37.15
0.2246	1.800	1.803	-32.01	-31.88
0.2248	1.788	1.791	-31.82	-31.92
0.3555	1.535	1.537	-26.85	-26.87
0.6143	1.331	1.343	-20.78	-20.95
0.6133	1.337	1.342	-21.13	-20.81
0.9812	1.230	1.234	-16.22	-16.62
0.9815	1.216	1.217	-16.88	-16.55
1.558	1.140	1.139	-12.88	-12.74

SECTION 5

CONVENTIONAL OSCILLATOR TESTS AT POWER5.0 SUMMARY

Oscillator experiments were performed at several power levels and coolant flows to demonstrate reactor stability, to provide data for comparison with the power coefficients determined from the static tests, and to provide for the determination of the frequency response of the fuel. As expected, the reactor was quite stable, and, as will be shown below, the experimental reactivity feedback was in good agreement with the model. The frequency response of the fuel temperature is currently being analyzed and will be reported at a later date. The conventional oscillator tests were performed at zero power, and at nominal power levels of 2 MW, 5 MW, 10 MW, 15 MW, 17 MW, and 19 MW. The zero power oscillator tests results are described in Section 4 while the at-power test results are discussed below.

5.1 DESCRIPTION OF THE EXPERIMENT

As with the zero power oscillator tests, the conventional oscillator tests were performed by oscillating a boron-carbide rod in the central dry well to produce sinusoidal oscillations in the reactivity, and thus in the neutron flux, fuel temperatures, coolant temperatures, etc. The time dependent rod position, signals from two (channel #27 and #28) of the operational neutron monitors located below the vessel, the time dependent fuel and coolant temperature oscillations indicated by the Instrumented Fuel Assemblies (IFA's) discussed in Section 2, and some of the vessel thermocouple signals were recorded on magnetic tape with the computerized data acquisition system. The sampling rate was controlled by the oscillator rod position so that 32 nearly equally spaced (in time) samples were recorded in each cycle of oscillation.

In all of the measurements the lower end of the oscillator rod was at an indicated mean height of 5.5 inches above the core mid-plane. This location was selected because oscillator rod worth measurements (see Appendix IV) had indicated a nearly linear relationship between reactivity

and rod position in this region of the core. In order to limit the amplitude of the power oscillations, the rod was oscillated about its mean position with an amplitude of $\lesssim 2$ inches. The actual amplitudes that were used for the various tests are listed in Appendix V. All amplitudes were converted to reactivities using a constant conversion factor of 2.736 cents per inch that was determined from the analysis (Section 4) of the zero power oscillator tests.

Up to eleven different frequencies of oscillation ranging between ~ 0.24 Hz and 0.0018 Hz were used for each set of oscillator data at a given power level and coolant flow, and the complete range of frequencies was repeated 2 or 3 times. Cyclic equilibrium was obtained at each frequency and several cycles of data were recorded on magnetic tape as one file of data. The number of cycles of data in each file ranged from a minimum of 3 cycles (in some instances) at low frequencies to a maximum of ~ 30 cycles at the higher frequencies. The nominal frequencies of oscillation used for the experiments are listed in Table 4-1.

The oscillator experiments were performed during the first extended period of operation at a given power level, and they were then repeated during the second period of extended operation at the same conditions in order to verify the reproducibility of the data. The former measurements are designated as Series A while the latter are designated as Series B. The experimental data are tabulated in Appendix V.

5.2 THEORETICAL MODEL

The oscillator test data is analyzed by comparing the measured frequency dependent reactivity feedback kernel, and the measured frequency dependent average coolant temperature to power transfer function with a theoretical model. The "measured" reactivity feedback kernel, $h(iw)$ at frequency w is determined from the calculated (based on experiment - Section 4) zero power reactivity transfer function G_o , and the measured at-power reactivity transfer function, G , through the following relation:

$$h(iw) = \frac{1}{P} \left[\frac{1}{G_o(iw)} - \frac{1}{G(iw)} \right]$$

In this relation P is the mean power level at which the oscillator test

was performed, while the other notation is given above. The transfer function between average core coolant temperature and power, $U(iw)$, is determined from the measured core inlet, $\Delta T_i(iw)$, core outlet, $\Delta T_o(iw)$, and power, $\Delta P(iw)$, oscillations according to the following relation

$$U(iw) = F_i(iw) \left[\frac{\Delta T_i(iw)}{\Delta P(iw)} \right] + [1 - F_i] \left[\frac{\Delta T_o(iw)}{\Delta P(iw)} \right]$$

In this expression F_i is a calculated function that depends on the frequency, the coolant flow, the shape of the axial power distribution in the core, the time constants of the fuel and coolant, etc. The expressions that are used for the calculation of this function are defined in reference 1. At low frequencies $F_i \sim 1/2$.

The theoretical model for the relation between the frequency dependent reactivity feedback and the average coolant temperature to power transfer function is described in reference 1. If the inlet temperature coefficient of reactivity is set to zero in accordance with the results of the static tests (Section 3) the model may be written as follows:

$$h(iw) = \alpha F_{av}(iw, \gamma, \nu) X_f(iw) + [C_f F_s(iw, \gamma, \nu) + C_q] U(iw)$$

In this model α is the power reactivity coefficient at a constant average coolant temperature, C_f and C_q are the fuel and core average coolant temperature reactivity coefficients respectively, $h(iw)$ is the feedback kernel discussed above, and the other quantities are defined as follows:

$F_{av}(iw, \gamma, \nu)$ = the frequency response of the average fuel temperature to a power oscillation at frequency w (normalized to unity at $w=0$).

$X_f(iw)$ = the frequency response of the ratio of the total power absorbed in the fuel to the "fission" power (normalized to unity at $w=0$). This function⁽¹⁾ is used to account for the frequency dependence of the delayed gamma heating.

$F_s(iw, \gamma, \nu)$ = the frequency response of the average fuel temperature to a coolant temperature oscillation at frequency w (normalized to unity at $w=0$).

$U(iw)$ = the measured frequency response of the average coolant temperature to a power oscillation at frequency w .
(defined above)

The mean power level used in the determination of $h(iw)$ is measured in units of MW and the parameter α thus has units of \$/MW. Accordingly, the parameters C_f and C_q have units of \$/°F, $U(iw)$ has units of °F/MW and the function F_{av} , F_s and X_f are dimensionless.

The frequency response functions F_{av} and F_s may be written as follows:

$$F_s = \frac{2J_1(x)/x}{J_0(x) + iw\gamma 2J_1(x)/x}$$

$$F_{av} = \frac{1}{iw(\gamma + v^2/8)} [1 - F_s]$$

where $J_0(x)$ and $J_1(x)$ are Bessel functions of the first kind of order zero and order one, respectively.

The argument x is defined as $x = i^{3/2} v\sqrt{w}$ where w is the frequency of oscillation in radians per second, $i = \sqrt{-1}$, and the parameters γ and v are defined in terms of fuel density, ρ , heat capacity, c , fuel conductivity, k , fuel pellet radius, R , and the effective heat transfer coefficient between fuel surface and coolant, h_f , as follows:

$$\gamma = \rho c R / 2h_f$$

$$v^2 = \rho c R^2 / k$$

A good approximation^(1,2) for F_{av} is

$$F_{av} \approx \frac{1}{1+iw\tau}$$

where the effective fuel time constant τ is defined as

$$\tau = \gamma + v^2/8$$

As noted in reference 1, the Doppler reactivity energy coefficient, η , can be determined from the above parameters according to the following expression

$$\eta = \frac{\alpha - C_p}{(\gamma + \nu^2/8)A_F}$$

where $C_p = -0.5\text{¢/MW}$ is the calculated non-Doppler component of the power reactivity coefficient, and where $A_F = 0.943$ is the calculated fraction of the total energy that is absorbed in the fuel.

5.3 MEASURED FEEDBACK AND COOLANT TEMPERATURE OSCILLATIONS

To fit the theoretical model to the data, measured values of the feedback kernel, h , and the average coolant to power transfer function, U , are required at a number of frequencies. The steps involved in the determination of these functions are described in detail in reference 1 and they will only be summarized here.

As discussed in Section 5.2, the feedback kernel is obtained from the measured power reactivity transfer function. To obtain this transfer function, the mean value of the flux signals and the harmonic components of the flux and oscillator rod position signals were determined from the recorded experimental data. The amplitude of the rod oscillation was converted to a reactivity oscillation by multiplying the measured displacements with the constant conversion factor of 2.736¢/inch that was determined from analysis (Section 4) of the zero power oscillator tests. The power reactivity transfer function was then calculated at all frequencies by dividing the fundamental component of the flux signal by the product of the flux mean value and the fundamental component of the reactivity oscillation.

As discussed in Section 5.2, the determination of the transfer function, $U(i\omega)$, between average core coolant temperature and power involves the measured response of the core inlet and outlet coolant temperatures. Because of inlet (see Section 2) and outlet thermocouple instrumentation problems, the correspondence between the true core average coolant temperature oscillations and the temperature oscillations indicated by thermocouples is questionable. However, even though no other* inlet thermocouple was available for comparison with the measured oscillations, the coolant inlet thermocouple in the central Instrumented Fuel Assembly (IFA) appeared to be working satisfactorily during the initial oscillator tests at power levels up to 10 MW. Subsequently however its performance,

*The inlet thermocouple in the outer IFA deteriorated early (see Section 2) while the vessel inlet resistance temperature detectors that were used for heat balance determinations in the static tests respond too slowly to be of use in the oscillator experiments. (Recent measurements using another inlet T/C in the vessel shroud region are currently being analyzed).

as demonstrated by the indicated mean temperature, appeared to deteriorate (see Section 2). However, the indicated oscillations about the mean value appeared to be reasonable, in general agreement with previous measurements, and since this was the only* inlet thermocouple available it was used in the determination of the average coolant temperature response.

The core coolant outlet temperature frequency response was usually determined from the temperature readings indicated by one of the two coolant outlet thermocouples in the central IFA. The frequency response of all IFA outlet coolant temperature thermocouples were in general agreement at all frequencies however, and on those occasions when the usual central IFA outlet thermocouple indicated an abnormally high mean value or unusual frequency response characteristics another IFA outlet thermocouple was used instead.

The data from the measured power reactivity transfer functions, feedback kernels, and transfer functions, $U(i\omega)$, between reactivity and core average coolant temperature are tabulated in Appendix V. Except at 2 MW, where data sets 2 and 3 of Series A show some variations, the power-reactivity appears quite reproducible. The variations in the 2 MW, Series A data sets 2 and 3 are primarily due to variations in the mean power from one frequency to the next. The coolant temperature oscillations at 2 MW were small and were treated as zero. The variations between data sets of the average coolant temperature to power transfer function were large, (50 to 100% in magnitude) particularly at the two lower power levels, and were much less reproducible than the power-reactivity transfer function (see below). Part of this non-reproducibility may be attributable to the instrumentation problems discussed above, and part may lie in the inherent difficulty of trying to determine temperature oscillations of only one to two °F out of the mean value of ~700°F. (Note that the power oscillations were of the order of $\pm 4\%$, so that at 5 MW a transfer function with a magnitude of 5°F/MW indicates that the temperature was oscillating only 1°F.

* Ibid.

Representative measured power reactivity transfer functions at different flows are compared with the zero power transfer functions in Figures 5-1 through 5-6, while the reproducibility of the power-reactivity transfer function is illustrated in Figures 5-7 through 5-16. As with the zero power transfer functions (See Section 4), the estimated standard deviation in the real and imaginary components of power reactivity transfer functions appears to be of the order of $\pm 1\frac{1}{2}\%$ at all frequencies. These curves illustrate that the at-power transfer functions approach the zero power transfer functions at the higher ($\gtrsim$ one radian per second) frequencies as the reactivity feedback approaches zero, and they also illustrate that the coolant flow has essentially no effect on the transfer function. Both effects are in agreement with the theoretical model.

Figure 5-1 Amplitude of the Power Reactivity Transfer Function at 5 MW

Figure 5-2 Phase of the Power Reactivity Transfer Function at 5 MW

Figure 5-3 Amplitude of Power Reactivity Transfer Function at 10 MW

Figure 5-4 Phase of the Power Reactivity Transfer Function at 10 MW

Figure 5-5 Amplitude of the Power Reactivity Transfer Function at 15 MW

Figure 5-6 Phase of the Power Reactivity Transfer Function at 15 MW

FIGURE 5-7 Amplitude of the Power Reactivity Transfer Function at 5 MW, 50% Flow

FIGURE 5-8 Phase of the Power Reactivity Transfer Function at 5 MW, 50% Flow

FIGURE 5-9 Amplitude of the Power Reactivity Transfer Function at 10 MW, 50% Flow

FIGURE 5-10 Phase of the Power Reactivity Transfer Function at 10 MW, 50% Flow

FIGURE 5-11 Amplitude of the Power Reactivity Transfer Function at 10 MW, 100% Flow

FIGURE 5-12 PHASE OF THE POWER REACTIVITY TRANSFER FUNCTION AT 10 MW, 100% FLOW

FIGURE 5-13 AMPLITUDE OF THE POWER TRANSFER REACTIVITY FUNCTION AT 15 MW, 75% FLOW, SERIES A

FIGURE 5-14 PHASE OF POWER REACTIVITY TRANSFER FUNCTION AT 15 MW, 75% FLOW, SERIES A

FIGURE 5-15 AMPLITUDE OF THE POWER TRANSFER REACTIVITY FUNCTION AT 17 MW

FIGURE 5-16 PHASE OF THE POWER TRANSFER REACTIVITY FUNCTION AT 17 MW

5.4 COMPARISON OF MEASURED AND THEORETICAL OSCILLATOR FEEDBACK

The theoretical model described in Section 5.2 was fit to the experimental data to determine "best estimates" of the power reactivity coefficient at a constant coolant temperature, α , the fuel temperature frequency response parameters γ and ν , and the reactivity energy coefficient. These parameters were determined by adjusting one or more of the parameters α , γ , or ν in the theoretical model described in Section 5.2 so that the sum of the weighted squares of the real and imaginary parts of a complex function $L(i\omega)$, that is defined as follows,

$$L(i\omega) = h(i\omega) - \alpha F_{av}(i\omega, \gamma, \nu) - [C_f F_s(i\omega, \gamma, \nu) + C_q] U(i\omega)$$

were a minimum. Note, that according to an equation in Section 5.2, $L(i\omega)$ would be identically zero if there were no statistical, or other, variations in the data, and if the model were an exact representation of the reactivity feedback.

The measured quantities in the above expression are the feedback kernel, $h(i\omega)$, and the average coolant temperature to power transfer function $U(i\omega)$. The other terms are calculated quantities that depend on the values of five parameters α , γ , ν , C_f , and C_q . In principal⁽¹⁾, "best" values for all five parameters can be determined by simultaneously minimizing the sum of the residuals defined above with respect to all the parameters. In practice a simpler approach was used.

First of all, the entire quantity $[C_f F_s(i\omega, \gamma_e, \nu_e) + C_q]$ was treated as a known function with known parameters by using estimated values (γ_e and ν_e) for the parameters in the function F_s , while for C_f and C_q calculated values, that are in agreement (see Section 3) with static test results were used. The indicated quantity was treated as known, rather than an unknown, for the following reasons: the coolant temperature oscillations were generally small (see Appendix V), and the last term in the expression for L was thus generally smaller by a factor of 4 or 5 than the measured feedback kernel $h(i\omega)$ and the calculated function $\alpha F_{av}(i\omega, \gamma, \nu)$; there was a rather large uncertainty in U (see Section 5.3) that might lead to a large uncertainty in the power coefficient α , if the

quantity $[C_f F_s + C_q]$ were treated as an unknown function to be determined by fitting of the data; in addition, such a treatment simplifies the analysis, as the above steps are equivalent to correcting the measured feedback kernel for the reactivity effects due to coolant temperature oscillation, and then fitting the fuel temperature reactivity model to the adjusted feedback.

Secondly, it was found during the analyses that even with the above simplifications, the values of α , and of the parameters γ and ν in F_{av} , could not all be simultaneously determined. The reason for this indeterminacy is that F_{av} is approximated quite well, as pointed out in Section 5.2, by $1/(1+i\omega\tau)$, where $\tau = \gamma + \nu^2/8$. Convergence was easily obtained however by treating one of the parameters in F_{av} , say γ , as known, and minimizing the residuals with respect to the other two parameters α , and ν in F_{av} . The goodness of fit (i.e. the weighted sum of the squares of the residuals), visual comparisons of the fits to the data, and the "best" values of α and the time constant were all very insensitive to large changes in the parameter, either γ or ν in F_{av} , which was treated as a known quantity. This is as would be expected in the domain for which $F_{av} \sim 1/[1+i\omega(\gamma+\nu^2/8)]$ is a good approximation. Although γ was the parameter which was generally held constant, consistent results were obtained when ν was treated as the known parameter.

During the fitting, a value of -0.15 $\text{c}/^\circ\text{F}$ was used for C_f and a value of -0.36 $\text{c}/^\circ\text{F}$ was used for C_q . The value of γ was generally about 12.0, but as indicated above, the values of τ and α are relatively insensitive to the value of γ . Although an extensive analysis to determine the sensitivity of α and τ to changes in C_f and C_q has not been performed, some analyses on the 15 MW data indicate the sensitivity is small. For example, a $\sim 25\%$ decrease in C_q caused a $\sim 4\%$ increase in α and less than 1% change in τ , while a $\sim 25\%$ decrease in C_f caused a $\sim 2\%$ increase in α and in τ .

The values of the parameters that were determined from the analysis are listed in Table 5-1. The tabulated Doppler energy coefficient was calculated from the fitted parameters using the expression in Section 5-2.

TABLE 5-1

CONVENTIONAL OSCILLATOR FITTED DATA BY INDIVIDUAL SET

Power (MW)	Flow (%)	Data Series and set	Power Coefficient α (¢/MW)	Time Constant τ (sec)	Doppler Energy Coefficient η (¢/MW-sec)
2	40	A1	-16.2	29.7	-0.56
2	40	A2	-16.8	29.3	-0.59
2	40	B1	-16.0	30.0	-0.55
2	40	B2	-16.3	31.3	-0.53
5	30	A1	-11.6	28.9	-0.41
5	30	A2	-10.9	27.0	-0.41
5	30	B	-11.0	29.0	-0.38
5	50	A1	-10.8	26.1	-0.42
5	50	A2	-11.6	28.2	-0.42
5	50	B	-11.4	28.8	-0.40
5	100	A1	-12.0	30.1	-0.41
5	100	A2	-11.7	26.9	-0.44
5	100	B	-11.3	26.9	-0.42

TABLE 5-1 (Continued)

CONVENTIONAL OSCILLATOR FITTED DATA BY INDIVIDUAL SET

Power (MW)	Flow (%)	Data Series and set	Power Coefficient α (ϕ /MW)	Time Constant τ (sec)	Doppler Energy Coefficient η (ϕ /MW-sec)
10	50	A1	-8.67	30.9	-0.28
10	50	A2	-8.50	28.2	-0.30
10	50	B	-8.55	28.8	-0.30
10	100	A1	-9.06	28.2	-0.32
10	100	A2	-8.84	27.9	-0.32
10	100	B	-8.85	28.4	-0.31
15	60	A1	-6.26	26.8	-0.23
15	60	A2	-6.38	27.3	-0.23
15	75	A1	-6.26	27.6	-0.22
15	75	A2	-6.33	29.2	-0.21
15	75	B	-6.11	27.1	-0.22
17	95	A1	-5.50	26.8	-0.20
17	95	A2	-5.49	26.6	-0.20
19	95	A	-4.65	24.5	-0.18

Fits of the theoretical model to the actual measured feedback kernel are illustrated in Figures 5-17 through 5-35. In these figures the "calculated" curves include the reactivity effects obtained using the measured coolant temperature oscillations and the calculated temperature reactivity coefficients discussed above; i.e., the calculated curves are plots of the function

$$\alpha_F F_{av} X_f + [C_f F_s + C_q] U$$

while the plotted points are measured values of the feedback kernel h .

The feedback kernels at 2 MW showed some variations between data sets as discussed in Section 5.3. At all other power levels the feedback kernels were consistently reproducible even though the average coolant temperature to power transfer functions, particularly at 5 MW, were not as reproducible, and changes (Appendix V) between one data set and the next were observed. The effect of different coolant temperature measurements (particularly the influence of variations at the higher frequencies) on the calculated curves is clearly illustrated for the 5 MW, 50% flow measurements in Figures 5-22 to 5-24. It is worth noting that in addition to instrumentation problems (Section 5.3), the actual amplitudes of the coolant temperature oscillations were small in these cases as they were $\leq \pm 1^\circ\text{F}$ to $\pm 2^\circ\text{F}$ out of a mean value of $\sim 760^\circ\text{F}$. This compares to a detection resolution of $\sim 0.25^\circ\text{F}$ and a noise level of the order of 0.25°F to 0.5°F . In contrast to the variations between "calculation" and experiment at 5 MW, 50% flow, the 10 MW, 100% flow measurements demonstrated consistency in both the feedback kernel and in the coolant temperature oscillations and the calculated curves (Figures 5-29 to 5-31) agreed very well with the measured feedback.

In Figures 5-36 to 5-41 the data in some of the previous graphs is presented in a different form to provide a comparison of the adjusted data that was actually fitted to the model for the fuel frequency response. These latter figures are a comparison of the curves of calculated fuel response $\alpha_f F_{av} X_f$ and the feedback kernels that have been adjusted for the

FIGURE 5-17 POWER REACTIVITY FEEDBACK KERNEL at 2 MW, SERIES A, SET 2 and 3

FIGURE 5-18 POWER REACTIVITY FEEDBACK KERNEL, AT 2 MW, SERIES B, SET 1

FIGURE 5-19 POWER REACTIVITY FEEDBACK KERNEL at 2 MW, SERIES B, SET 2 and 3

FIGURE 5-20 POWER REACTIVITY FEEDBACK KERNEL AT 5 MW, 30% FLOW, SERIES A, SET 2

FIGURE 5-21 POWER REACTIVITY FEEDBACK KERNEL AT 5 MW, 30% FLOW, SERIES B

FIGURE 5-22 POWER REACTIVITY FEEDBACK KERNEL AT 5 MW, 50% FLOW, SERIES A, SET 1

FIGURE 5-23 POWER REACTIVITY FEEDBACK KERNEL AT 5 MW, 50% FLOW, SERIES A, SET 2

FIGURE 5-24 POWER REACTIVITY FEEDBACK KERNEL 5 MW, 50% FLOW, SERIES B

FIGURE 5-25 POWER REACTIVITY FEEDBACK KERNEL AT 5 MW, 100% FLOW, SERIES A, SET 2

FIGURE 5-26 POWER REACTIVITY FEEDBACK KERNEL AT 5 MW, 100% FLOW, SERIES B

FIGURE 5-27 POWER REACTIVITY FEEDBACK KERNEL AT 10 MW, 50% FLOW, SERIES A, SET 2

FIGURE 5-28 POWER REACTIVITY FEEDBACK KERNEL FOR 10 MW, 50% FLOW, SERIES B

FIGURE 5-29 POWER REACTIVITY FEEDBACK KERNEL AT 10 MW, 100% FLOW, SERIES A, SET 1

FIGURE 5-30 POWER REACTIVITY FEEDBACK KERNEL AT 10 MW, 100% FLOW, SERIES A, SET 2

FIGURE 5-31 POWER REACTIVITY FEEDBACK KERNEL AT 10 MW, 100% FLOW, SERIES B

FIGURE 5-32 POWER REACTIVITY FEEDBACK KERNEL AT 15 MW, 60% FLOW

FIGURE 5-33 POWER REACTIVITY FEEDBACK KERNEL AT 15 MW, 75% FLOW, SERIES A

FIGURE 5-34 POWER REACTIVITY FEEDBACK KERNEL AT 17 MW

FIGURE 5-35 POWER REACTIVITY FEEDBACK KERNEL AT 19 MW

FIGURE 5-36 Calculated Fuel Response Vs. Adjusted Feedback at 5 MW, 50% Flow, Series A, Set 1

FIGURE 5-37 Calculated Fuel Response Vs. Adjusted Feedback at 5 MW, 50% Flow, Series A, Set 2

FIGURE 5-38 Calculated Fuel Response Vs. Adjusted Feedback at 5 MW, 50% Flow, Series B

FIGURE 5-39 CALCULATED FUEL RESPONSE VS. ADJUSTED FEEDBACK AT 10 MW, 100% FLOW, SERIES B

FIGURE 5-40 CALCULATED FUEL RESPONSE VS. ADJUSTED FEEDBACK AT 15 MW, 60% FLOW , SET 2

FIGURE 5-41. CALCULATED FUEL RESPONSE VS. ADJUSTED FEEDBACK AT 17 MW, SET 1

coolant temperature reactivity effects; i.e. the adjusted data points, h_c , are obtained from the measured feedback kernel h , the measured coolant temperature to power transfer function U , and the calculated expression (see above) $C_f F_s + C_q$ according to the following relation:

$$h_c = h - [C_f F_s + C_q]U$$

To determine the influence of the coolant temperature oscillations on the fitted parameters α and τ , several cases were ran in which the reactivity corrections due to the coolant temperature oscillations were arbitrarily set equal to zero. Two of these cases, one at 15 MW and the other at 19 MW, are compared in Figures 5-42 and 5-43 with the ordinary fits in which coolant temperature corrections are included. As the figures indicate, the curves with no coolant temperature effects do a poorer job (particularly at lower frequencies) of approximating the experimental data than do the curves in which the coolant temperature effects are incorporated. In all cases, reduction of the coolant temperature oscillations to zero caused an increase in the fitted fuel time constant and an increase in the magnitude of the power reactivity coefficient.

The averaged power coefficient and fuel time constant that were obtained from all the data at a given power level are tabulated in Table 5-2, along with the Doppler energy coefficient that was obtained from these parameters using the formula in Section 5.2. The estimated standard deviations in the fitted parameters include the effect of an estimated 5% uncertainty in absolute power level. Also included are the observed average deviation in the mean values of α and τ : these were taken as 0.2¢/MW at power levels below 5 MW and 0.1¢/MW at the higher power levels, and as 0.8 sec, respectively. In addition, the deviations include, somewhat arbitrarily, approximately 40% of the change introduced in the parameters when the coolant temperature oscillations were set equal to zero. The actual deviations in α for this effect were taken as 6% at 2, 5, and 10 MW, as 9% at 15 and 17 MW and as 12% at 19 MW, while the deviation in τ for the effect of coolant temperature variations was taken as 2.0 sec. Data from some of the balanced⁽¹⁾ oscillator tests where the coolant temperature oscillations are minimized are currently being analyzed, and these results may provide a better indication of the actual uncertainties in the above parameters.

FIGURE 5-42 POWER REACTIVITY FEEDBACK KERNEL AT 15 MW, 60% Flow, (Coolant Temperature Effects)

FIGURE 5-43 Power Reactivity Feedback Kernel at 19 MW, (Coolant Temperature Effects)

TABLE 5-2

AVERAGED CONVENTIONAL OSCILLATOR PARAMETERS

Power (MW)	Power Coefficient α (ϕ /MW)	Time Constant τ (sec)	Doppler Energy Coefficient η (ϕ /MW-sec)
2	-16.3 $\pm$ 1.3	30.1 $\pm$ 2.2	-0.56 $\pm$ 0.06
5	-11.4 $\pm$ 0.9	28.0 $\pm$ 2.2	-0.41 $\pm$ 0.05
10	- 8.8 $\pm$ 0.7	28.7 $\pm$ 2.2	-0.30 $\pm$ 0.03
15	- 6.2 $\pm$ 0.7	28.0 $\pm$ 2.2	-0.22 $\pm$ 0.03
17	- 5.5 $\pm$ 0.6	26.7 $\pm$ 2.2	-0.20 $\pm$ 0.03
19	- 4.7 $\pm$ 0.6	24.5 $\pm$ 2.2	-0.18 $\pm$ 0.03

SECTION 6

COMPARISON OF CALCULATION AND EXPERIMENT6.1 SUMMARY

The Doppler reactivity effect has been measured in SEFOR at fuel temperatures up to the vicinity of fuel melting under fuel operating conditions characteristic of those that will be encountered in operating power reactors. During the experiments the fuel temperatures ranged between a minimum of 350°F and a maximum of approximately 4800°F as the operating conditions varied between zero power at a 350°F coolant temperature and a power level of 20 MW at an average core coolant temperature of 760°F. Analysis of the static and time dependent experimental data provided a measured power-Doppler reactivity relationship having an estimated standard deviation of $\pm 8\%$. Comparison of the results with calculations demonstrated that the Doppler component of the feedback can be described by a fuel temperature coefficient $T \frac{dk}{dT}$ of -0.0081 with an estimated standard deviation of ± 0.0014 . This coefficient compares favorably with the value* of -0.0085 that was predicted⁽¹⁾ prior to the measurements.

Since the SEFOR fuel was designed⁽²⁾ to suppress fuel axial expansion reactivity effects, most ($\sim 95\%$) of the reactivity effects due to fuel temperature changes are a result of Doppler broadening of the nuclear cross sections. All of the experimental results from steady state and oscillatory tests at power levels up to 20 MW have shown, in agreement with calculation, that the only other significant reactivity effects are those associated with changes in the average core coolant temperature. Measurements to determine reactivity effects other than those associated with the fuel temperature and the average coolant temperature were those performed to determine the reactivity effects associated with changes in the coolant inlet temperature (at a constant power and average coolant temperature) and in the reflector temperatures. The results of these

*See footnote of page 1-4.

measurements are described in Section 3.3 and in Appendix III. The coefficients were, in agreement with calculations⁽¹⁾, nearly zero.

The results of the time dependent oscillator tests were also used to provide a rough estimate of the Doppler energy coefficient to be expected from sub-prompt and super-prompt transients which will be performed at a later date. Because of the non constant fuel thermal conductivity and fuel to cladding heat transfer coefficient, these estimates are rather crude however, and the results obtained from analysis of the fast transients are expected to yield larger reactivity energy coefficients than those estimated from the slowly varying temperature oscillations.

6.2 INTEGRAL DOPPLER REACTIVITY EFFECTS

The data in Table 3-11 demonstrate the dependence of the measured Doppler reactivity changes on the reactor power level. Since the Doppler reactivity effect is caused by changes in fuel temperature rather than the power per se, the relationship between total power and local fuel temperatures throughout the core must be known before the measured Doppler power-reactivity changes can be compared to the calculated values. To make this comparison, the fuel thermal conductivity, fuel-to-clad gap coefficient, power distribution, etc., that are discussed in Section 2 were used in the WEDOP⁽³⁾ program to calculate local fuel temperatures throughout the core for various total reactor power levels. The local reactivity effect introduced by local fuel temperature changes was then calculated by the WEDOP⁽³⁾ program under the assumption that the local change in reactivity is proportional to the logarithm of the local temperature change. (A logarithmic total change corresponds to a differential change having a constant value for $T \frac{dk}{dT}$.) Since previous analyses⁽⁴⁾ have shown that a power squared weighting is a good approximation to the more accurate flux-adjoint weighting, the total core Doppler reactivity changes were then calculated using a power-squared weighting of the local reactivity effects.

The reactivity changes for a Doppler $T \frac{dk}{dT}$ of -0.0081 that were obtained from the WEDOP⁽³⁾ calculations are compared with the measured Doppler reactivity effects in Figure 6-1. It is seen that the agreement between measured and calculated effects as a function of reactor power is quite good.

FIGURE 6-1 DOPPLER POWER REACTIVITY MEASUREMENTS

The WEDOP⁽³⁾ program was also used to calculate the Doppler component of the change in reactivity that occurs when the coolant temperature is changed while the power level is held constant. These calculated results were combined with the previously⁽¹⁾ calculated non-Doppler coolant coefficient of $-0.35\text{¢}/^{\circ}\text{F}$ and are compared with the measured results in Table 6-1. As with the power-reactivity measurements noted above, the agreement between calculations using a Doppler $T \frac{dk}{dT}$ of -0.0081 and experiment is good. In these cases, however, the Doppler effect is less than half the total measured change, and the comparison of results is more dependent upon the magnitude of the non-Doppler contribution.

TABLE 6-1

MEASURED AND CALCULATED REACTIVITY EFFECTS AT CONSTANT POWER

Power (MW)	Average Core Coolant Temperature (°F)	Calculated* Non-Doppler Effect (¢)	Calculated* Doppler Effect (¢)	Total Calculated* Reactivity Change (¢)	Total Measured** Reactivity Change (¢)
0	760	0.0	0	0	0
0	650	38.5	23.4	61.9	62
0	550	73.5	46.8	120	120
0	350	143.5	101.4	245	248
5	760.0	0	0	0	0
5	604.0	54.6	26.6	81.2	83.4
5	603.6	54.7	26.9	81.6	83.7
5	500.6	90.8	46.4	137	139
5	401.8	125.4	67.4	193	198
10	760.0	0	0	0	0
10	559.4	70.2	33.0	103	104

* The calculated total non-Doppler effect is a constant $-0.35\text{¢}/^{\circ}\text{F}$. The Doppler contribution was calculated with the WEDOP⁽³⁾ program using a Doppler $T\frac{dk}{dT}$ of -0.0081 .

** The measured values at power were taken from Table 3-12 while the zero power values were taken from Reference 1.

6.3 DOPPLER POWER REACTIVITY COEFFICIENTS

The Doppler components of the power reactivity coefficients obtained from analysis of the static and oscillator tests are summarized and compared with calculations in Table 6-2. The tabulated measured values were obtained from the values in Table 3-15 and 5-3 by correcting for the calculated^(1,2) fuel and fuel clad axial expansion reactivity effect of $-0.5\text{c}/\text{MW}$. The calculated coefficients were obtained from results of the WEDOP⁽³⁾ code using the fuel temperature power relations discussed in the previous section.

The oscillator, static, and calculated coefficients agree reasonably well at every power level, and they all demonstrate the same general decreasing magnitude with increasing power level. Although the magnitude of the coefficient obtained from the oscillator tests is larger at low power and appears to decrease more rapidly with increasing power than does the static test coefficient, the magnitude and trend of the calculated coefficient lies between the coefficients obtained from the two different types of measurements. This over all agreement throughout the complete power range illustrates that the static and time dependent behavior of the system are in agreement, and along with the integral measurements of the previous section, that the reactivity effects are adequately described with a model for the fuel temperature Doppler coefficient that subscribes a constant value of -0.0081 to the absolute fuel temperature reactivity term $T \frac{dk}{dT}$.

TABLE 6-2

DOPPLER POWER REACTIVITY COEFFICIENTS

Power Level (MW)	Oscillator tests (¢/MW)	Doppler Coefficient	
		Static tests (¢/MW)	Calculated $T \frac{dk}{dT} = -0.0081$ (¢/MW)
0	-	-16.8±1.7	-
2	-15.8±1.3	-14.4±1.2	-15.5
5	-10.9±0.9	-11.6±0.8	-11.1
10	- 8.3±0.7	- 8.5±0.6	- 7.6
15	- 5.7±0.7	- 6.5±0.6	- 6.0
17	- 5.0±0.6	- 5.9±0.6	- 5.6
19	- 4.2±0.6	- 5.4±0.7	- 5.1
20	-	- 5.2±0.8	- 5.0

6.4 TIME CONSTANTS AND ENERGY COEFFICIENTS

The fuel time constant is defined in Section 5.2 as

$$\tau = \gamma + v^2/8 = \frac{\rho CR^2}{2h_f R} + \frac{\rho CR^2}{8K}$$

where ρ , C , and K are the fuel density average heat capacity, and average fuel thermal conductivity respectively, where R is the fuel pellet radius, and where h_f is the effective fuel to coolant heat transfer coefficient. At steady state the temperature difference, ΔT , between the average fuel and coolant temperature is related to the fuel rod power density, Q , by

$$\Delta T = QR^2 \left(\frac{1}{8K} + \frac{1}{2h_f R} \right)$$

Thus, the fuel time constant can be expressed as

$$\tau = \rho C \Delta T / Q$$

and for the average location in the core

$$\tau = \frac{MC\Delta T}{A_f \Delta P}$$

where M is the mass of fuel ($\text{PuO}_2\text{-UO}_2$) in the core, ΔP is the total power, and $A_f = 0.943$ is the fraction of the total heat that is absorbed in the fuel.

The above expression was used to calculate the fuel time constants at different reactor power levels. The core fuel loading was 2120 Kg of $\text{PuO}_2\text{-UO}_2$. The expression for the heat capacity that was used in the calculation is $C = 0.165 + 1.31 \times 10^{-6} (T-700)$ w-sec/g-°F where T is the fuel temperature in °F. The "effective" average fuel temperature rise, ΔT , for use in the expression for τ was defined so that $-0.0081 \ln [1+\Delta T/1220]$ was equal to the reactivity change calculated using the WEDOP⁽³⁾ code. At the higher power levels, the calculated effective temperature rise was about 3%

larger than the calculated actual core average fuel temperature rise. The calculated and measured time constants are tabulated in Table 6-3. As the results in the table indicate, the calculated and measured fuel times constants agree within about 10%.

The Doppler energy coefficient η , which is equal to the change in Doppler reactivity ΔK_D per unit change in energy $\Delta E = MC\delta T$ deposited in the fuel, can be expressed as

$$\eta = \frac{\Delta K_D}{\Delta E} = \frac{1}{MC} \left(\frac{\Delta K_D}{\delta T} \right) = \frac{1}{MC} \left(\frac{\Delta K_D}{\Delta P} \right) \left(\frac{\Delta P}{\delta T} \right)$$

where M, and C are defined above, and where δT is the change in effective Doppler fuel temperature. From the above definitions it would appear that the energy coefficient can be expressed in terms of the Doppler power coefficient $\alpha = \Delta K_D / \Delta P$, and the fuel time constant τ , i.e.

$$\eta = \frac{\alpha}{A_f \tau}$$

This expression was used to calculate the energy coefficients using the measured Doppler power coefficients from the previous section and the measured fuel time constants in Table 6-3. The results are listed under Doppler energy coefficients - Oscillator Tests in Table 6-3. The values in the adjacent column of Table 6-3 was obtained from the corresponding calculated values. These results agree with the measured values.

However, the use of parameters α and τ determined from relatively slow system changes to provide a prediction of the energy coefficient that would be observed from rapid changes is valid only if the fuel heat capacity and fuel to coolant heat transfer coefficient are constant and if the flux-adjoint weighted logarithmic temperature behavior of Doppler coefficient for slow power changes is similar to that observed during rapid power changes. This is not the case, as is demonstrated by the values in the last column of Table 6-3, which were calculated from the definition $\eta = \Delta K_D / \Delta E$ using the WEDOP code: they differ significantly from the values calculated using the fuel time constants. The WEDOP values are expected to be more representative of the actual energy coefficients which will be measured during the subsequent transient tests.

TABLE 6-3

FUEL TIME CONSTANTS AND ENERGY COEFFICIENTS

Power (MW)	Fuel Time Constants		Doppler Oscillator Tests	Energy Coefficients	
	Oscillator Tests	Calculated		Calculated	From *
	(sec)	(sec)	(¢/MW-sec)	From Time Constants (¢/MW-sec)	Definition (¢/MW-sec)
2	30.1±2.2	32.6	-0.56±0.06	-0.51	-0.54
5	28.0±2.2	31.6	-0.41±0.05	-0.38	-0.45
10	28.7±2.2	29.0	-0.30±0.03	-0.28	-0.37
15	28.0±2.2	27.5	-0.22±0.03	-0.24	-0.33
17	26.7±2.2	27.0	-0.20±0.02	-0.22	-0.31
19	24.5±2.2	26.5	-0.18±0.03	-0.20	-0.29

*Calculated using the WEDOP⁽³⁾ program. These are the expected values for subsequent transient tests.

6.5 UNCERTAINTIES IN THE DOPPLER TEMPERATURE COEFFICIENT

The overall estimated standard deviation in the measured Doppler reactivity effects as a function of reactor power level is $\pm 8\%$. This deviation is composed of the $\pm 4\%$ standard deviation of the Doppler component of the static reactivity measurements as discussed in Section 3.4, an estimated $\pm 5\%$ uncertainty in the absolute value of the indicated power levels, and one-half ($\pm 5\%$) of the indicated average deviation ($\pm 10\%$) in the power reactivity coefficients. A portion of the average deviation in the power coefficients was included in the overall Doppler uncertainty to account, at least to some extent, for the observed variations between the coefficients from static and oscillator tests. Only one-half of the deviations in the power coefficients were included, because portions of these deviations are attributable to power and reactivity deviations that are incorporated (above) into the other components of the overall uncertainty. The $\pm 8\%$ deviation is the square root of the sum of the squares of the above individual components (i.e., random deviations are assumed).

The overall estimated standard deviation in the Doppler temperature coefficient $T \frac{dk}{dT}$ is $\pm 17\%$. One component of this deviation is the $\pm 8\%$ deviation in the power-Doppler reactivity relationship. The other component, and the primary contributor to the deviation, is an estimated $\pm 15\%$ uncertainty in the calculated relationship between power level and effective core average fuel temperature, resulting from an estimated $\pm 15\%$ uncertainty in the fuel thermal conductivity. Since the model for the fuel-clad gap coefficient was normalized to the fuel temperature measurements using the best estimate for the fuel thermal conductivity, no additional uncertainty was added to the power-temperature relationship for uncertainties in the fuel-clad gap coefficient. This would not appear to be too gross an assumption, since the temperature drop across the fuel-clad gap is small compared to the drop across the fuel pellet, particularly at high power levels (see Figure 2-3).

Although the generally good early agreement between calculated and measured fuel temperatures in the central instrumented fuel assembly would indicate that the uncertainty in the fuel temperature - power relationship might be as small as $\pm 10\%$ or less, the large deviation between measured and calculated temperatures in the peripheral instrumented fuel assembly at power levels above 5 MW would appear to negate such a reduction in the uncertainty.

The contributions of other deviations, such as a $\pm 3\%$ deviation in local power density⁽²⁾ and a $\pm 2\%$ variation in pellet density (allowed by fuel specification) are small compared to the $\pm 15\%$ uncertainty in the fuel thermal conductivity and may be neglected. The various contributions to the total estimated standard deviation are summarized in Table 6-4.

Table 6-4

STANDARD DEVIATION IN DOPPLER COEFFICIENT

<u>Parameter</u>	<u>Effect on Doppler Coefficient</u>
Absolute Reactivity Measurement	$\pm 4\%$
Absolute Power Level Measurement	$\pm 5\%$
Deviations in Power Coefficients	<u>$\pm 5\%$</u>
Total Power Reactivity Deviation	$\pm 8\%$
Uncertainty in Fuel Thermal conductivity	$\pm 15\%$
Uncertainty in Fuel to Clad Heat Transfer	0*
Uncertainty in local Power Density	$\pm 3\%$
Variations in Fuel Pellet Density	$\pm 2\%$
Uncertainties in Coolant and Clad Heat Transfer Properties	<u>0†</u>
Total Power Fuel Temperature Deviation	$\pm 15\%$
Total Deviation	$\pm 17\%$

*The actual uncertainty in the heat transfer coefficient may be 40%, but its effect on the Doppler coefficient has been minimized by normalization to measured fuel temperatures.

†Large uncertainties in the parameters have little influence on fuel temperatures.

APPENDIX I

CORE LOADINGS AND FINE REFLECTOR CALIBRATION

I-1 CORE LOADINGS

All reactivity measurements, other than reflector calibrations, described in this report were performed on a core having either the loading configuration illustrated in Figure I-2 or that illustrated in Figure I-3. The first of these loadings was designated Assembly I-I and the second Assembly I-J. All at power measurements prior to August 21, 1970 were performed on Assembly I-I, and those after this date were performed on Assembly I-J. The change in loading from I-I to I-J was accomplished by replacing a B_4C rod in core location W3.0-S2.0E with a stainless steel rod. This replacement provided additional (36.1 cents) reactivity to offset the reactivity feedback introduced by operation at high power.

In addition to the core loadings noted above, two other core loadings are of interest since they provide additional reflector calibration measurements which served to demonstrate the independence of reflector worth on coolant temperature and influence of a shortening of the stroke of the fine reflectors (see below). The first of these loadings was designated Assembly I-G and the second Assembly I-H. In Assembly I-G (Figure I-1) there were eight vacant (sodium filled) fuel rod locations, and three vacant tightener rod locations. Assembly I-H was obtained from loading in Assembly I-G by placing fuel and tightener rods in the vacant locations. A loading diagram for this core is not shown since it is identical, except for the central dry well, to the subsequent loading Assembly I-I. The measured reactivity worth of the central dry well was $\sim +3$ cents.

FIGURE I-1. CORE LOADING FOR ASSEMBLY I-G

FIGURE I-2 CORE LOADING FOR ASSEMBLY I-1

FIGURE I-3 CORE LOADING FOR ASSEMBLY I-J

I.2 FINE REFLECTOR CALIBRATIONS

The magnitude of most reactivity changes between different steady state reactor conditions in SEFOR are determined from the observed changes in positions of the two calibrated fine reflectors, Number 3, and Number 8. These reflectors were calibrated using the asymptotic period technique described below. Earlier calibrations are described in reference 1. The calibration data that were used to determine "static" reactivity effects discussed in this report, as well as additional calibrations that were performed to determine the influence of coolant temperature and reflector modifications are tabulated in Tables I-1 through I-7.

The reflector calibrations using the asymptotic period technique were performed in the following manner: The reactor was brought to critical at low power (~600 watts) with the fine reflector to be calibrated in the completely lowered position and the other fine reflector in the completely raised position. A coarse reflector configuration was selected to maintain criticality and to minimize the influence of a lowered coarse reflector on the fine reflector calibration (i.e., the coarse reflectors immediately adjacent to the fine reflectors were maintained in the completely raised position). The reflector to be calibrated was raised a few centimeters to produce an asymptotic period of the order of 100 seconds, the period was measured, and the other fine reflector was lowered to bring the reactor back to critical at the original flux level. This process was repeated until the entire length of a fine reflector had been calibrated. The accuracy in the period measurements is estimated ⁽¹⁾ to be ~1%.

Earlier ⁽¹⁾ reflector worth measurements demonstrated that the worth of a fine reflector is slightly dependent on the configuration of other reflectors even when the reflectors adjacent to a fine reflector are always maintained in the completely raised position. To provide calibration curves for the different coarse reflector configurations

TABLE I-1

REFLECTOR No. 8 CALIBRATION-ASSEMBLY I-I
(550°F)

Reflector No. 5 Down and No. 10 at 43 cm

Reflector No. 8 (cm)		Period (sec)	Reactivity (ρ)
From	To		
1.03	9.58	125.23	7.191
9.58	18.38	76.18	10.613
18.38	25.01	84.40	9.822
25.01	30.32	96.52	8.855
30.32	35.26	98.10	8.743
35.26	40.01	98.83	8.693
40.01	44.73	97.67	8.773
44.73	49.49	96.66	8.845
49.49	54.30	97.09	8.814
54.30	59.51	95.22	8.950
59.51	65.67	83.68	9.886
65.67	71.52	104.89	8.294
71.52	77.96	112.30	7.849
77.96	85.01	138.79	6.608
85.01	98.16	144.99	6.371

TABLE I-2

REFLECTOR NO. 3 CALIBRATION-ASSEMBLY I-I
(760°F)

REFLECTOR No. 10 at 38 cm

Reflector No. 3 (cm)		Period (sec)	Reactivity (β)
FROM	TO		
1.04	9.50	120.90	7.400
9.50	16.98	95.94	8.897
16.98	23.13	93.63	9.067
23.13	28.47	93.92	9.046
28.47	33.52	93.78	9.056
33.52	38.54	89.01	9.429
38.54	43.02	103.01	8.413
43.02	47.51	102.43	8.451
47.51	52.12	100.70	8.566
52.12	57.08	99.26	8.664
57.08	62.58	90.31	9.324
62.58	68.68	89.74	9.371
68.68	73.69	136.84	6.686
73.69	80.91	110.22	7.972
80.91	89.11	150.40	6.180
89.11	97.68	303.18	3.345

TABLE I-3

REFLECTOR NO. 8 CALIBRATION - ASSEMBLY I-I
(760°F)

REFLECTOR No. 5 at 36 CM

Reflector No. 8 (cm)		Period (sec)	Reactivity (¢)
FROM	TO		
1.02	9.63	117.17	7.592
9.63	17.04	96.83	8.835
17.04	23.74	84.42	9.822
23.74	29.15	97.38	8.794
29.15	34.35	90.46	9.313
34.35	39.11	95.94	8.897
39.11	43.73	95.94	8.897
43.73	48.73	87.86	9.525
48.73	53.56	94.35	9.014
53.56	58.57	96.68	8.843
58.57	64.01	94.52	9.000
64.01	69.70	100.43	8.583
69.70	75.92	106.93	8.168
75.92	82.99	125.40	7.184
82.99	90.00	197.84	4.889
90.00	98.18	350.79	2.929

TABLE I-4

REFLECTOR NO. 8 CALIBRATION-ASSEMBLY I-G
(370°F)

Reflector No. 5 at 95 cm

Reflector No. 8 (cm)		Period (sec)	Reactivity (ρ)
From	To		
0.65	9.10	135.50	6.740
9.10	17.83	82.83	9.964
17.83	24.38	89.61	9.381
24.38	29.52	103.90	8.357
29.52	34.51	97.11	8.813
34.51	39.27	94.37	9.013
39.27	43.71	104.33	8.329
43.71	48.56	89.32	9.405
48.56	53.33	94.66	8.991
53.33	58.47	89.18	9.416
58.47	64.72	76.05	10.625
64.72	71.49	81.39	10.098
71.49	79.85	77.78	10.448
79.85	88.61	119.34	7.479
88.61	98.18	229.00	4.300

TABLE I-5

REFLECTOR 3 CALIBRATION - ASSEMBLY I-I

(370°F)

Reflectors No. 5 and No. 10 Down, and No. 6 at 42.9 cm

Reflector No. 3 From To (cm)	Doubling Time (sec)	Reactivity (cents)
00.16 10.11	82.8	7.471
10.11 17.95	69.0	8.642
17.95 25.07	58.4	9.834
25.07 30.06	78.8	7.776
30.06 35.14	69.5	8.593
35.14 40.06	68.9	8.652
40.06 44.97	66.8	8.864
44.97 49.94	66.0	8.948
49.94 55.13	63.8	9.1875
55.13 59.64	81.8	7.545
59.64 66.09	56.5	10.084
66.09 72.05	74.0	8.177
72.05 78.62	81.4	7.576
78.62 87.06	86.8	7.190
87.06 95.17	168.3	4.083

TABLE I-6

REFLECTOR 8 CALIBRATION - ASSEMBLY I-I

(370°F)

Reflectors No. 5 and No. 10 Down and No. 6 at 40.8 cm

Reflector No. 8 From To (cm)	Doubling Time (sec)	Reactivity (cents)
00.42 9.51	89.9	6.987
9.51 17.08	76.8	7.939
17.08 23.51	71.6	8.395
23.51 28.96	75.3	8.065
28.96 34.06	73.7	8.205
34.06 38.76	76.5	7.965
38.76 43.42	75.5	8.049
43.42 48.05	75.9	8.0145
48.05 52.59	82.5	7.494
52.59 57.48	75.8	8.023
57.48 64.01	56.3	10.112
64.01 71.47	55.8	10.181
71.47 79.99	61.4	9.465
79.99 88.63	100.6	6.366
88.63 95.27	275.0	2.614

TABLE I-7

REFLECTOR NO. 3 CALIBRATION-ASSEMBLY I-H
(370°F)

Reflector No. 5 and No. 10 Down and No. 6 at 46 cm

Reflector No. 3 (cm)		Period (sec)	Reactivity (ç)
From	To		
0.4	8.96	152.35	6.113
8.96	17.07	100.84	8.556
17.07	23.57	98.53	8.713
23.57	29.11	101.42	8.517
29.11	34.08	107.62	8.126
34.08	38.86	100.12	8.604
38.86	43.75	95.94	8.897
43.75	48.17	110.37	7.965
48.17	52.69	116.28	7.637
52.69	58.07	91.90	9.200
58.07	64.16	83.39	9.913
64.16	70.40	94.06	9.035
70.40	77.35	100.70	8.566
77.35	85.12	121.62	7.364
85.12	97.67	146.87	6.304

expected during operation at power, the fine reflectors were calibrated with the configurations that resulted during zero power operations at $\sim 350^{\circ}\text{F}$, $\sim 550^{\circ}\text{F}$, and $\sim 700^{\circ}\text{F}$. In addition, to determine whether the core coolant temperature influenced (independent of reflector configuration) reflector worth, the core loading was changed so that calibrations could be performed under similar reflector configurations, but with different core coolant temperatures.

The calibrations at $\sim 550^{\circ}\text{F}$ and $\sim 750^{\circ}\text{F}$ in Assembly I-I (Figure I-2) are listed in Tables I-1 through I-3. Additional calibrations to determine any influence of core coolant temperature, independent of reflector configuration, were performed on Assembly I-G at 350°F . The calibration data for reflector No. 8, and the coarse reflector configuration for this core are tabulated in Table I-4.

The coarse reflector configuration for the calibration of fine reflector number 8 in Assembly I-G at $\sim 350^{\circ}\text{F}$ is similar to that used for the calibration of number 8 in Assembly I-I at $\sim 750^{\circ}\text{F}$. The core coolant temperatures are considerably different however, and any reflector worth differences resulting from core expansion, sodium density changes, relative position of core and reflectors, or other effects associated with changes in core sodium temperature should evidence themselves in these two calibrations. The two calibrations are compared in Figure I-4. The comparison shows that within the accuracy of measurement ($\sim 1\%$) there is no difference in the shape or total reflector worth of the two calibration curves, and thus no change in worth characteristics as a result of sodium temperature changes per se.

In addition to the above measurements, the fine reflectors were recalibrated after an outage to replace thermocouples in the reflector region. The stroke of each fine reflector was reduced approximately 3 centimeters, out of a ~ 100 centimeter stroke, when the thermocouples were replaced. The recalibration was performed to determine whether the slight reduction in stroke had altered previous calibrations. Within the $\sim 1\%$ accuracy of the calibrations no change was observed in the shape of the

FIGURE I-4 FINE REFLECTOR CALIBRATIONS AT TWO DIFFERENT COOLANT TEMPERATURES

worth versus position curves, and only a slight (1 to 1.5 cent) reduction in total worth resulted from the modification. This lack of change is evidenced by a comparison of the recalibration data in Table I-5 and I-6 with the previous⁽¹⁾ calibration of reflector number 8 in Assembly I-F, (Note that in comparing these two the change in the inhour equation described in Appendix II must be accounted for) and with the calibration of reflector number 3 in Assembly I-H that is tabulated in Table I-7.

During most of the tests described in this report, all coarse reflectors were always completely raised, and criticality was achieved by adjusting the positions of the two fine reflectors. The calibration curves that more nearly approximated the at-power configurations were those for reflectors No. 3 and No. 8 in Assembly I-I at $\sim 760^{\circ}\text{F}$ (Note - see above - that the calibration curve for No. 8 in Assembly I-G could also have been used with essentially no change in measured results).

The fine reflector calibration curves for reflectors number 3 and number 8 in Assembly I-I at $\sim 760^{\circ}\text{F}$ were thus used for measurements of all static changes in reactivity described in this report except for the data at the lower coolant temperature discussed in Section 3.5. For the measurements at a nominal power of 5 MW and coolant temperatures of $\sim 600^{\circ}\text{F}$ and $\sim 500^{\circ}\text{F}$, the calibration curve for reflector No. 8 in Assembly I-I at 550°F was used for both reflector 3 and 8. (Other measurements, such as in Assembly I-I at $\sim 760^{\circ}\text{F}$, had indicated the calibration curves for No. 3 and No. 8 were nearly the same). At 5 MW and $\sim 400^{\circ}\text{F}$ the calibration curve for Assembly I-F (reference 1) was used - this curve is nearly identical to the curve for No. 8 in Assembly I-I at $\sim 370^{\circ}\text{F}$.

APPENDIX II

REACTIVITY CONVERSION FORMULAS FOR SEFOR

The value of the effective delayed neutron fraction β , and the inhour equation that are used in this report are compared below with the values which were previously ⁽¹⁾ used prior to October 1, 1970. The newer quantities are based on the analysis of the zero power oscillator tests. They provide consistency between static and oscillator test results, as well as a more accurate evaluation of reactivity effects that are measured and calculated in units of dollars.

The new value of β is 0.00327. This is 3.8% larger than the previously ⁽¹⁾ used calculated value of 0.00315. Those previously reported calculated reactivity effects that are expressed in units of dollars or cents should thus be decreased by 3.8% to reflect the change in β . The magnitude of previously reported measured reactivity effects should be decreased (see below) by 2.3% to account for the change in the inhour equation. These two changes cause a 1.5% increase in the magnitude of previously reported ratios of measured to calculated reactivity effects.

The newer conversion formulas are based on the fitted delayed neutron parameters obtained from the analysis of the zero power oscillator tests reported in Section 4. The estimated value of β obtained from this analysis is 0.00327. This is 3.8% higher than the previously used calculated value of 0.00315. Since calculated reactivity effects must be divided by β to convert to units of dollars, previously calculated values that are expressed in dollar units may be updated by decreasing their magnitude 3.8%. Calculated reactivity values which are expressed in absolute or percentage units are unaffected by the change in β .

All measured reactivity values in SEFOR are reported in units of dollars or cents. These values are based, either directly, or indirectly through the calibrated reflector control, on the relationship between measured asymptotic reactor period and reactivity. This relationship, the inhour equation, involves the same delayed neutron parameters as the zero power reactivity transfer function. The parameters in the fit of the theoretical model to the measured zero power reactivity transfer

function are tabulated in Section 4. These parameters were used in the inhour equation⁽¹⁾ and compared with the previously⁽¹⁾ used parameters that were based on calculated neutron contributions from the fissionable isotopes. The resulting relationships between asymptotic period and reactivity are compared in Table II-1.

All of the reactivity measurements in SEFOR, including the calibrations of reflector segments which are used in turn to measure reactivity changes, are made⁽¹⁾ with reactor periods between ~ 80 and ~ 450 seconds, with the majority of these having periods of ~ 100 seconds with a measurement accuracy of $\sim 1\%$. The data in Table II-1 show that for a 100 second period, the new conversion formula gives a reactivity that is 2.3% less than the old. The tabulated values also show that the ratio of the reactivity obtained from the new inhour equation to the reactivity obtained from the old equation is essentially constant (within 0.2%) over the range of periods between ~ 80 and ~ 500 seconds. The constancy of this ratio allows all previously reported measured reactivity values to be updated by applying only one reduction factor of 2.3%. It also allows the previously determined relationships between reactivity and reflector position to be used for future measurements provided the reactivity values are reduced by 2.3%.

When the new value of β and the new inhour equation are used to convert a measured reactivity in dollars to a reactivity in absolute units, the number is $\sim 1.5\%$ larger, as indicated by the last column of Table II-1 for a 100 second period, than was previously the case. The last column also illustrates the increase necessary to update the magnitude of previously (prior to October 1, 1970) reported ratios of measured to calculated reactivity effects.

TABLE II-1

COMPARISON OF NEW AND OLD SEFOR
REACTIVITY CONVERSION FORMULAS

$$\beta_{\text{new}} = 0.00327$$

$$\beta_{\text{old}} = 0.00315$$

<u>Period (sec)</u>	<u>Reactivity (ρ)*</u>		<u>K_{new}/K_{old}</u>	<u>K_{new}β_{new}/K_{old}β_{old}</u>
	<u>K_{new}</u>	<u>K_{old}</u>		
50	14.360	14.669	0.9789	1.016
60	12.643	12.920	0.9786	1.016
70	11.306	11.558	0.9782	1.015
80	10.233	10.464	0.9779	1.015
90	9.3512	9.5648	0.9777	1.015
100	8.6125	8.8110	0.9775	1.015
200	4.8382	4.9546	0.9765	1.014
300	3.3727	3.4552	0.9761	1.013
400	2.5902	2.6541	0.9759	1.013
500	2.1029	2.1551	0.9758	1.013
600	1.7702	1.8142	0.9757	1.013

*Calculated from inhour equation using the new and old delayed neutron parameters respectively.

APPENDIX III

REFLECTOR TEMPERATURE REACTIVITY COEFFICIENTSSUMMARY

The SEFOR reflector temperature coefficient of reactivity was measured at power levels of 5, 10, 15, and 20 MW. The maximum observed change in reactivity at any power level due to temperature changes^{*} in excess of 100°F was 1.1 cents. At all power levels the reactivity appeared to decrease slightly with increasing reflector temperature. The magnitudes of the reactivity changes were less than the estimated standard deviation (Section 3.2) in reactivity at power however, and for all practical purposes the reflector temperature coefficient of reactivity may be treated as zero.

REFLECTOR TEMPERATURE MEASUREMENTS AND ANALYSIS

To enable the determination of the Doppler coefficient, a number of experiments are performed in SEFOR to determine the relationship between reflector position (reactivity) and plant variables such as vessel inlet temperature, flow, etc. The measurements described here were performed to determine the relationship between reactivity and the temperature of the radial reflectors. In these experiments the reflector temperature was first increased by decreasing the gas coolant flow around the reflectors. The reflector temperature was then decreased by increasing the gas flow to its original value. During the measurements a fine reflector position was adjusted to maintain a constant flux level. The average variation in flux level was held to 1 or 2 parts in 500, or less, while the variation

* These temperature changes were measured by thermocouples located near the center of a raised coarse reflector.

in average core coolant (sodium) temperature during the measurements was held to less than 1°F. The small reactivity corrections for coolant temperature variations were accounted for. The flux variations were less than the estimated deviation (Section 3.2) in flux level and reactivity corrections for these variations were neglected.

The averages of data taken at low and high equilibrium reflector temperature readings are shown in Table III-1. The data in each set are averages of 3 to 5 successive measurements with the data acquisition system static test program.* The long wait between equilibrium conditions was necessitated by the slow response of reflector temperature to changes in gas coolant flow. The time dependent response of thermocouple no. 56 between steady state values of 290°F and 149°F is shown in Figure III-1 for a rapid increase from 40% to 100% coolant gas flow at time zero during the 5 MW tests. The response to a decrease in flow was even slower.

The reflector temperature readings shown in Table III-1 were taken from two thermocouples located near the center of coarse reflector number six. This reflector was maintained in the completely raised position during the measurements and the thermocouples were in the vicinity of the peak reflector gamma and neutron flux. As a result of their location these thermocouples are among those most responsive to power and gas coolant flow changes, and the observed temperatures were indicative of the highest temperatures in the reflector region.

The data of Table III-1 indicate that the core reactivity decreases very slightly with increasing reflector temperature, and that the effect is about $-0.01\text{¢}/^{\circ}\text{F}$ or less when the temperature is monitored by these particular thermocouples. The measured reactivity changes are less than the estimated (Section 3.2) standard deviation ($\pm 1.6\text{¢}$) in reactivity measurements at power however, and since the normal changes in reflector temperature between zero power and full power are $\sim 200^{\circ}\text{F}$ or less, the reflector temperature coefficient may be treated as zero.

*The data for reflector thermocouple No. 60 were taken from Test Plan Procedure II-8 data sheets for all three sets of measurements at 5 MW.

TABLE III-1

REFLECTOR TEMPERATURE - REACTIVITY MEASUREMENTS

Time (1970- 1971)	Nominal Power (MW)	Data Set Number	Average Coolant Temperature (°F)	Reflector No. 3 Position (cm)	Worth (¢)	Reflector Thermocouple No. 56 (°F)	Reflector Thermocouple No. 60 (°F)	Relative* Reactivity at 760°F (¢)
7/9-1400	5	1	760.4	42.20	-59.76	152	130	+0.10
7/10-0250	5	3	759.9	42.17	-59.71	149	128	-0.10
7/10-0035	5	2	760.8	42.94	-61.15	290	252	-1.08
8/14-1615	10	1	760.9	70.00	-107.75	215	181	-0.44
8/14-1920	10	2	761.7	69.85	-107.54	199	167	+0.16
8/14-2115	10	3	761.8	69.91	-107.62	231	194	+0.12
8/15-0450	10	5	761.6	69.80	-107.48	197	164	+0.17
8/15-0230	10	4	761.7	70.50	-108.40	322	273	-0.70
8/29-1400	15	2	759.8	50.96	-76.19	257	205	0.0
8/29-1055	15	1	759.5	51.42	-77.12	479	395	-1.07
8/29-1740	15	3	759.5	51.46	-77.11	441	362	-1.06
1/29-2220	20	1	750.8	67.00†	-103.16†	309	240	-0.14
1/30-0640	20	3	751.2	66.96†	-103.10†	315	247	+0.10
1/30-1050	20	4	751.9	67.20†	-103.46†	308	241	+0.05
1/30-0450	20	2	752.1	67.64†	-104.11†	472	377	-0.52

*Reactivity corrections to a 760°F average coolant temperature were calculated using reactivity coefficients of -0.50, -0.47, -0.46, and -0.44¢/°F at 5, 10, 15, and 20 MW respectively. The relative values were adjusted at each power level so that the average of the values at the cooler reflector temperatures are zero.

†Values for Reflector No. 8.

FIGURE III-1 RESPONSE OF A REFLECTOR T/C TO A RAPID INCREASE
IN COOLANT FLOW

APPENDIX IV

OSCILLATOR ROD CALIBRATION

Prior to the zero power oscillator tests, the reactivity worth of the oscillator rod was measured as a function of rod position above the core midplane to determine a region where the reactivity worth varied in a linear manner with rod position. A sufficiently linear relationship was observed when the tip of the rod was ~ 5.5 inches above the midplane, and the tip of the rod was oscillated about this position during the oscillator tests.

The worth versus oscillator rod position measurements were made with a calibrated fine reflector. Measurements were made as the rod was lowered by increments into the core, and the measurements were repeated as the rod was withdrawn from the core. The data are tabulated in Table IV-1. The worth of the rod at an indicated position of -1.74 inches was determined at a different time than the other values. Therefore, the tabulated value for this position was obtained by adding the average measured incremental worth from 0.26 inches to the previously measured total worth at 0.26 inches.

The differential oscillator rod worth (cents/inch) with the lower tip of the rod at an indicated position of 5.5 inches above the core midplane was determined from a four point interpolation formula using the test data in Table IV-1. The differential worth obtained from these static tests was then compared to the differential worth obtained from analysis of the zero power oscillator tests. The results (see Table IV-2) differed by $\sim 15\%$. To check these measurements the oscillator rod was recalibrated using the asymptotic period technique.

The results of the third set of measurements using the "period technique" are shown in Table IV-3. They are compared with the previous reflector swap measurements and with a calculation in Figure IV-1. The calculated curve is a reactivity perturbation calculation obtained using

the BISYN^(2,3) flux synthesis program and is normalized to a value of 33.2¢ at the indicated zero position. The incremental worths, cents/inch, for the different techniques with the lower tip of the rod at an indicated position of 5.5 inches are listed in Table IV-2.

As the data in Table IV-2 indicates, the average incremental worth from the reflector swap and asymptotic period measurements is about 10% less than the incremental worth obtained from the oscillator tests. Although the mean values disagree by more than the indicated uncertainties, the uncertainty bands overlap, and there is apparently no reason to believe that the difference in the incremental worths obtained from the different measurement techniques is significant to the determination of the Doppler coefficient.

TABLE IV-1

OSCILLATOR ROD CALIBRATION

Rod* Position (inches)	Reflector Position (cm)	No. 3 Worth*** (¢)	Temperature (°F)	Worth** to 741.5°F (¢)	Change† in Worth (¢)
20.19	30.57	38.11	741.5	38.11	-0.09
18.00	30.80	38.52	742.0	38.25	-0.23
16.00	31.29	39.40	742.0	39.13	-1.11
14.00	32.17	41.00	742.0	40.72	-2.70
12.00	33.64	43.68	742.5	43.15	-5.13
10.00	35.44	47.04	742.75	46.36	-8.34
8.00	37.86	51.60	743.5	50.53	-12.51
6.00	40.25	56.10	743.5	55.02	-17.00
4.00	42.73	60.75	742.5	60.21	-22.19
2.00	44.77	64.60	741.75	64.47	-26.45
0.26	47.42	69.58	740.0	70.39	-32.37
2.00	45.07	65.16	741.5	65.16	-27.14
4.00	42.52	60.36	742.0	60.09	-22.07
6.00	39.95	55.53	741.75	55.39	-17.37
8.00	37.60	51.11	741.5	51.11	-13.09
10.00	34.89	46.01	741.5	46.01	-7.99
12.00	33.28	43.02	741.5	43.02	-5.00
14.00	32.17	41.00	742.25	40.60	-2.58
16.00	31.53	39.83	743.0	39.02	-1.00
18.00	31.17	39.19	743.0	38.38	-0.36
20.19	31.22	39.28	744.0	37.93	+0.09
0.26	47.01	68.83	762.0	67.71+++	
-1.74	50.69	75.71	762.0	74.59+++	-39.22++
0.26	47.19	69.16	762.5	67.77+++	

* Indicated distance above the core midplane of the lower end of the 26-inch long poison oscillator rod. When the indicated position is zero, the actual position of the lower tip of the rod is estimated to be 1 7/8 inches below core midplane, and the estimated position of the lower end of the B₄C region of the rod is 5/16 inches below the core midplane.

** Corrected for temperature effects using a temperature coefficient of -0.54¢/°F.

*** Worths determined using the calibration curve for Assembly I-I @750°F in Appendix I.

† Relative to the average worth, in the adjacent column, at 20.19 inches.

++ Normalized by adding -6.85¢ (as indicated by the data in the adjacent column) to the value of -32.37¢ at 0.26 inches.

+++ These worths are relative to 760°F.

TABLE IV-2

DIFFERENTIAL OSCILLATOR ROD WORTH

WITH TIP AT 5.5 INCHES

<u>Measurement</u>	<u>Incremental Worth (¢/in.)</u>
Reflector Swap (inserting rod)	2.62
Reflector Swap (withdrawing rod)	2.30
Asymptotic Period	<u>2.55</u>
Average	$2.49 \pm 0.19^*$
Zero Power Transfer Function	$2.74 \pm 0.11^{**}$

*This is 1.96 times the square root of one sixth of the sum of the squares of the individual deviations from the mean, and is essentially the estimated standard deviation in the mean for a system with only two degrees of freedom.

** See Section 4.

TABLE IV-3

OSCILLATOR ROD WORTH FROM PERIOD MEASUREMENTS

Change in Oscillator Rod Position*		Doubling Time (sec)	Incremental Reactivity Change (¢)	Oscillator Rod Position	Cumulative Reactivity Worth (¢)
From (in.)	To (in.)				
0.04	2.50	85.7	7.26	20.00	0.00
2.50	5.00	95.5	6.65	13.00	-3.74
5.00	7.50	104.6	6.16	10.00	-8.25
7.50	10.00	130.4	5.10	7.50	-13.35
10.00	13.00	150.5	4.51	5.00	-19.51
13.00	20.00	185.5	3.74	2.50	-26.16
				0.04	-33.42

*This is the indicated position (see footnote at bottom of Table IV-1).

APPENDIX V

OSCILLATOR TEST DATA

The conventional oscillator tests at power (see Section 5) were performed with eleven different frequencies of oscillation over a frequency range between approximately 0.25 and 0.0018 Hz. The nominal frequencies of oscillation are tabulated in Table V-1. The oscillation frequencies could not be exactly reproduced between one set of measurements and the next however, and the actual frequency for a given test was determined from the experimental data by recording the time (accurate to $\pm 100\mu\text{sec}$) at each data sampling point and utilizing the fact that 32 samples were recorded (see Section 5) for each cycle of oscillation. Once a frequency had been established, the maximum variation in frequency between one cycle and the next was $\leq 1\%$ at the lowest frequencies, and the variation decreased to less than 0.1% at the highest frequencies.

All the time dependent oscillation data, such as time, rod position, flux, temperatures, etc., were recorded on magnetic tape. The nominal amplitude of the rod oscillation (the actual value was recorded on the tape), as well as the tape and file^{*} numbers for each set of data are tabulated for reference purposes in Tables V-2-A to V-2-0.

The measured power reactivity transfer functions and the feedback kernels that were determined from the at-power data and the zero power transfer function of Section 4 are tabulated in Tables V-3 to V-28. The estimated standard deviation in the real and imaginary parts of the measured power reactivity transfer functions is $\sim 1\frac{1}{2}\%$ at all frequencies. Unless otherwise indicated power channel 28 (wide range monitor number 2) was used in determining the transfer functions.

The measured average (as determined from measured inlet and outlet

*Each file contains data from several successive cycles of oscillation at the same frequency.

temperature oscillations according to the relation in Section 5) coolant temperature to power transfer functions are tabulated in Tables V-29 to V-43. The coolant oscillations at 2 MW were very small and were treated as zero. The reproducibility (and lack of it) the accuracy of these measurements, and the instrumentation used are discussed in Section 5.

TABLE V-1

NOMINAL FREQUENCIES OF OSCILLATION

<u>Designation</u>	<u>Radians/Second</u>	<u>Hertz</u>
F2	1.56	0.25
F3	0.98	0.16
F4	0.61	0.097
F5	0.35	0.056
F6	0.22	0.035
S1	0.13	0.021
S2	0.078	0.0125
S3	0.049	0.0078
S4	0.031	0.0049
S5	0.018	0.0029
S6	0.011	0.00175

TABLE V-2-A
OSCILLATOR AMPLITUDES AND RECORDS

2 MW, Series A, 40% Flow

Set #1 (Tape #62)			Set #2 (Tape #62)			Set #3 (Tape #62)		
Frequency	Rod Amplitude (inches)	File No.	Frequency	Rod Amplitude (inches)	File No.	Frequency	Rod Amplitude (inches)	File No.
F2	2.0	7	F2	2.0	21	S5	0.67	37
F3	2.0	8	F3	2.0	22	S4	0.67	38
F4	2.0	9	F4	2.0	23	S3	0.67	39
F4	1.5	10	F4	1.5	24	S2	0.67	40
F5	1.5	11	F5	1.5	25	S1	0.67	41
F6	1.5	12	F6	1.5	26	F6	0.67	42
F6	1.0	13	F6	1.0	27	F6	1.0	43
S1	1.0	14	S1	1.0	28			
S2	1.0	15	S2	1.0	29			
S3	1.0	16	S2	0.8	30			
S3	0.6	17	S3	0.8	31			
S4	0.6	18	S3	0.6	32			
S5	0.6	19	S4	0.6	33			
S6	0.6	20	S5	0.6	34			
			S5	0.6	35			
			S6	0.6	36			

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TABLE V-2-B
OSCILLATOR AMPLITUDES AND RECORDS

2 MW, Series B, 40% Flow

Set 1 (Tape #93)			Set 2 (Tape #93)			Set 3 (Tape #93)		
Frequency	Rod Amplitude	File No.	Frequency	Rod Amplitude	File No.	Frequency	Rod Amplitude	File No.
F2	2.0 inches	12	F3	2.0 inches	27	F2	2.0 inches	40
F3	2.0	13	F4	2.0	28	F3	2.0	41
F4	2.0	14	F4	1.5	29	F4	2.0	42
F4	1.5	15	F5	1.5	30	F4	1.5	43
F5	1.5	16	F6	1.5	31	F5	1.5	44
F6	1.5	17	F6	1.0	32	F6	1.5	45
F6	1.0	18	S1	1.0	33	F6	1.0	46
S1	1.0	19	S2	1.0	34			
S2	1.0	20	S3	1.0	35			
S3	1.0	21	S3	0.6	36			
S3	0.6	22	S4	0.6	37			
S4	0.6	23	S5	0.6	38			
S5	0.6	24	S6	0.6	39			

TABLE V-2-C
OSCILLATOR AMPLITUDES AND RECORDS

5 MW, 30% Flow

Series A Set 1 (Tape #79)			Series A Set 2 (Tape #79)			Series B Set 1 & 2 (Tape #78)		
Frequency	Rod Amplitude	File No.	Frequency	Rod Amplitude	File No.	Frequency	Rod Amplitude	File No.
F2	1.2 inches	16	F2	1.2 inches	33	F2	1.2 inches	45
F3	1.2	15	F3	1.2	32	F3	1.2	46
F4	1.2	14	F4	1.2	31	F4	1.2	47
F5	1.2	13	F5	1.2	30	F5	1.2	48
F6	1.2	12	F6	1.2	29	F6	1.2	49
S1	1.2	17	S1	1.2	28	S1	1.2	50
S2	1.2	18	S2	1.2	27	S2	1.2	51
S3	1.2	19	S3	1.2	26	S3	1.2	52
S4	1.2	20	S3	1.2	25	S4	1.2	53
S5	1.2	21	S4	1.2	34	S5	1.2	54
S6	1.2	22	S5	1.2	24	S6	1.2	55
			S6	1.2	23	S5	1.2	56
						S1	1.2	57
						S3	1.2	58

TABLE V-2-D

OSCILLATOR AMPLITUDES AND RECORDS

5 MW, 50% Flow

Series A, Set 1 (Tape #72)			Series A, Set 2 (Tape #72)			Series B, Set 1 and 2 (Tape #78)		
<u>Frequency</u>	<u>Rod Amplitude</u>	<u>File No.</u>	<u>Frequency</u>	<u>Rod Amplitude</u>	<u>File No.</u>	<u>Frequency</u>	<u>Rod Amplitude</u>	<u>File No</u>
S1	1.2 inches	13	F2	1.2 inches	30	F2	1.2 inches	3
F2	1.2	14	S1	1.2	31	F3	1.2	4
S2	1.2	15	F3	1.2	32	F4	1.2	5
F3	1.2	16	S2	1.2	33	F5	1.2	6
S4	1.2	20	F4	1.2	34	F6	1.2	7
F6	1.2	21	S3	1.2	35	S1	1.2	8
S6	1.2	25	F5	1.2	36	S3	1.2	10
S3	1.2	26	F6	1.2	37	S4	1.2	11
S4	1.2	27	S5	1.2	38	S5	1.2	12
			S6	1.2	39	S6	1.2	13
			S4	1.2	40	F2	1.2	14
						F4	1.2	15
						F6	1.2	16
						S2	1.2	17
						S4	1.2	18
						S6	1.2	19

TABLE V-2-E
OSCILLATOR AMPLITUDES AND RECORDS

5 MW, 100% Flow, Series A

Set #1 (Tape #73)			Set #2 (Tape #73)		
Frequency	Rod Amplitude	File No.	Frequency	Rod Amplitude	File No.
F2	1.2 inches	23	F3	1.2 inches	32
F3	1.2	19	F4	1.2	33
F4	1.2	12	F5	1.2	34
F5	1.2	16	F6	1.2	35
F6	1.2	15	S1	1.2	25
S1	1.2	24	S2	1.2	26
S2	1.2	22	S3	1.2	27
S3	1.2	21	S4	1.2	28
S4	1.2	20	S5	1.2	29
S5	1.2	17	S6	1.2	37
S6	1.2	14			

TABLE V-2-F
OSCILLATOR AMPLITUDES AND RECORDS

5 MW, 100% Flow, Series B

Set 1 (Tape #78)			Set 2 (Tape #78)		
Frequency	Rod Amplitude	File No.	Frequency	Rod Amplitude	File No.
F2	1.2 inches	24	F2	1.2 inches	35
F3	1.2	25	F4	1.2	36
F4	1.2	26	F6	1.2	37
F5	1.2	27	S2	1.2	38
F6	1.2	28	S4	1.2	39
S1	1.2	29	S6	1.2	40
S2	1.2	30			
S4	1.2	32			
S5	1.2	33			
S6	1.2	34			

TABLE V-2-G
OSCILLATOR AMPLITUDES AND RECORDS

10 MW, 50% Flow, Series A

Set 1 (Tape #26)			Set 2 (Tape #26)		
<u>Frequency</u>	<u>Rod Amplitude</u>	<u>File No.</u>	<u>Frequency</u>	<u>Rod Amplitude</u>	<u>File No.</u>
F2	1.4 inches	12	F2	1.4 inches	23
F3	1.4	13	F4	1.4	25
F5	1.4	15	F5	1.4	26
F6	1.4	16	F6	1.4	27
S1	1.4	17	S1	1.4	28
S2	1.4	18	S2	1.4	29
S3	1.4	19	S3	1.4	30
S4	1.4	20	S4	1.4	31
S5	1.4	21	S5	1.4	32
S6	1.4	22	S6	1.4	33

TABLE V-2-H
OSCILLATOR AMPLITUDES AND RECORDS

10 MW, 50% Flow, Series B

Set 1 & 2 (Tape #65)		
<u>Frequency</u>	<u>Rod Amplitude</u>	<u>File No.</u>
F2	1.4 inches	3
F3	1.4	4
F4	1.4	5
F5	1.4	6
F6	1.4	7
S1	1.4	8
S2	1.4	9
S3	1.4	10
S4	1.4	11
S5	1.4	12
S6	1.4	13
F2	1.4	14
F4	1.4	15
F6	1.4	16
S2	1.4	17
S4	1.4	18
S6	1.4	19

TABLE V-2-I
OSCILLATOR AMPLITUDES AND RECORDS
 10 MW, 100% Flow, Series A

Set 1 (Tape #32)			Set 2 (Tape #32)		
Frequency	Rod Amplitude	File No.	Frequency	Rod Amplitude	File No.
F2	1.4 inches	12	F2	1.4 inches	23
F3	1.4	13	F3	1.4	24
F4	1.4	14	F4	1.4	25
F5	1.4	15	F5	1.4	26
F6	1.4	16	F6	1.4	27
S1	1.4	17	S1	1.4	28
S2	1.4	18	S2	1.4	29
S3	1.4	19	S3	1.4	30
S4	1.4	20	S4	1.4	31
S5	1.4	21	S5	1.4	32
S6	1.4	22	S6	1.4	33

TABLE V-2-J
OSCILLATOR AMPLITUDES AND RECORDS

10 MW, 100% Flow, Series B

Set 1 (Tape #65)			Set 2 (Tape #65)		
Frequency	Rod Amplitude	File No.	Frequency	Rod Amplitude	File No.
F2	1.4 inches	24	S5	1.4 inches	35
F3	1.4	25	S3	1.4	36
F4	1.4	26	S1	1.4	37
F5	1.4	27	F5	1.4	38
F6	1.4	28	F3	1.4	39
S2	1.4	30			
S3	1.4	31			
S4	1.4	32			
S5	1.4	33			

TABLE V-2-K
OSCILLATOR AMPLITUDES AND RECORDS

15 MW, 60% Flow

Set 1 Tapes 41 & 47 Rod Amplitude			Set 2 Tape 47 Rod Amplitude		
Frequency	(inches)	File No.	Frequency	(inches)	File No.
F2	1.4	46	S6	1.4	4
F3	1.4	47	S5	1.4	5
F4	1.4	48	S4	1.4	6
F5	1.4	49	S3	1.4	7
F6	1.4	50	S2	1.4	8
S1	1.4	51	S1	1.4	9
S2	1.4	52	F6	1.4	10
S3	1.4	53	F5	1.4	11
S5	1.4	2	F4	1.4	12
S6	1.4	3	F3	1.4	13
			F2	1.4	14

TABLE V-2-L
OSCILLATOR AMPLITUDES AND RECORDS
 15 MW, 75% Flow, Series A

Set 1 Tape 41			Set 2 Tape 41		
Frequency	Rod Amplitude (inches)	File No.	Frequency	Rod Amplitude (inches)	File No.
F2	1.4	12	F2	1.4	24
F3	1.4	13	F3	1.4	25
F4	1.4	14	F4	1.4	26
F5	1.4	15	F5	1.4	27
F6	1.4	16	F6	1.4	28
S1	1.4	17	S1	1.4	29
S2	1.4	18	S2	1.4	30
S3	1.4	20	S3	1.4	31
S4	1.4	21	S4	1.4	32
S5	1.4	22	S5	1.4	33
S6	1.4	23	S6	1.4	34

TABLE V-2-M
OSCILLATOR AMPLITUDES AND RECORDS
15 MW, 75% Flow, Series B

Tape Number 115

<u>Frequency</u>	<u>Rod Amplitude</u>	<u>File Number</u>
F2	1.40	12
F3	1.40	13
F4	1.40	14
F5	1.40	15
F6	1.40	16
S2	1.40	18
S3	1.40	19
S4	1.40	20
S5	1.40	21
S6	1.40	22
F2	1.40	23
F3	1.40	24
F4	1.40	25
F6	1.40	26
S2	1.40	27
S4	1.40	28
S6	1.40	29
F3	1.40	30

TABLE V-2-N
OSCILLATOR AMPLITUDES AND RECORDS
 17 MW, 75% Flow, Series A

Frequency	Set 1 Tapes 65 & 55		Frequency	Set 2 Tape 55	
	Rod Amplitude	File No.		Rod Amplitude	File No.
S6	1.45	53	S6	1.45	6
S5	1.45	54	S5	1.45	7
S4	1.45	55	S4	1.45	8
S3	1.45	56	S3	1.45	9
S2	1.45	57	S2	1.45	10
S1	1.45	58	S1	1.45	11
F5	1.45	2	F6	1.45	12
F4	1.45	3	F5	1.45	13
F3	1.45	4	F4	1.45	14
F2	1.45	5	F3	1.45	15
			F2	1.45	16

TABLE V-2-0

OSCILLATOR AMPLITUDES AND RECORDS

19 MW

Tape Number 94

<u>Frequency</u>	<u>Rod Amplitude</u>	<u>File Number</u>
F2	1.00	1
F3	0.86	2
F4	0.80	3
F5	0.65	4
F6	0.58	5
F2	1.20	6
F3	1.20	7
F4	1.20	8
F5	0.85	9
F6	0.85	10
S1	0.85	11
S2	0.85	12
S3	0.85	13
S4	1.25	14
S5	1.25	15
S6	1.25	16
F2	1.20	17
F4	1.20	18
F6	0.85	19

TABLE V-3
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
2 MW 40% Flow (Set #1, Series A)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power) (cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.555	1.118	-12.79	0.003632	187.0
0.9518	1.193	-16.02	0.006771	148.5
0.570	1.317	-20.09	0.01119	122.0
0.5875	1.300	-20.34	0.008592	143.5
0.337	1.517	-24.60	0.019211	119.3
0.1933	1.900	-28.20	0.28295	111.4
0.1603	2.058	-28.54	0.3264	109.3
0.1292	2.294	-27.87	0.04033	109.4
0.07742	2.845	-22.17	0.06307	116.5
0.0480	3.181	-13.04	0.09084	126.3
0.0481	3.157	-13.03	0.09129	127.0
0.0300	3.243	- 4.21	0.12049	134.0
0.01669	3.190	0.08	0.1428	150.0
0.01038	3.282	4.42	0.1495	153.3

TABLE V-4
 POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
 2 MW, 40% Flow (Set #2 and #3, Series A)
 Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude ($\frac{\text{percent power}}{\text{cents reactivity}}$)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5641	1.085	-12.56	0.01707	186.63
0.9760	1.164	-15.99	0.01387	180.70
0.6073	1.266	-19.80	0.01495	165.51
0.6057	1.268	-19.79	0.01499	164.20
0.3479	1.481	-24.99	0.01609	137.20
0.2194	1.810	-27.81	0.02535	105.84
0.2178	1.786	-27.84	0.02497	115.82
0.1301	2.310	-27.53	0.04186	106.55
0.07870	2.843	-21.65	0.06460	115.39
0.07870	2.945	-22.67	0.06147	109.87
0.04937	3.245	-12.41	0.09077	122.78
0.04934	3.203	-12.50	0.09128	124.04
0.03096	3.226	- 3.49	0.1141	138.23
0.01787	3.067	0.90	0.1481	148.96
0.01796	3.310	0.30	0.1370	146.89
0.01134	3.196	3.45	0.1518	155.18
0.01755	3.235	0.06	0.1422	149.06
0.03030	3.263	- 4.39	0.1210	136.80
0.04880	3.228	-12.84	0.09114	125.60
0.07787	2.867	-22.24	0.06296	117.60
0.1292	2.298	-27.79	0.04029	114.06
0.2165	1.790	-28.10	0.02427	127.30
0.2170	1.797	-27.81	0.02541	123.73

TABLE V-5
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
2 MW, 40% (Set #1, Series A)
Power Channel 27

Frequency rad/sec	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.555	1.106	-12.79	0.008826	169.56
0.9518	1.184	-15.92	0.009816	160.45
0.570	1.305	-20.23	0.01157	139.91
0.5875	1.308	-20.00	0.007449	136.80
0.337	1.512	-25.28	0.01884	117.22
0.1933	1.919	-28.50	0.02749	103.38
0.1603	2.038	-28.26	0.03368	115.52
0.1292	2.276	-27.82	0.04031	111.81
0.07742	2.837	-22.11	0.06330	117.13
0.0480	3.173	-13.03	0.09101	126.53
0.0481	3.181	-12.92	0.09110	126.15
0.0300	3.276	- 4.50	0.1189	136.07
0.01669	3.239	- 0.01	0.1406	149.77
0.01038	3.332	+ 4.85	0.1478	154.60

TABLE V-6
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
2 MW, 40% (Set #2 and #3, Series A)
Power Channel 27

Frequency (rad/sec)	<u>Power-Reactivity Transfer Function</u>		<u>Feedback Kernel</u>	
	<u>Amplitude (percent power) (cents reactivity)</u>	<u>Phase (degrees)</u>	<u>Amplitude (\$/MW)</u>	<u>Phase (degrees)</u>
1.5641	1.079	-12.66	0.01980	189.77
0.9760	1.157	-15.66	0.01715	175.03
0.6073	1.277	-19.87	0.01208	158.43
0.6057	1.260	-19.98	0.01627	172.70
0.3479	1.472	-24.83	0.01777	141.96
0.2194	1.785	-27.74	0.02517	114.40
0.2178	1.765	-27.73	0.02560	123.38
0.1301	2.270	-27.60	0.04105	111.70
0.07870	2.869	-21.96	0.06358	114.01
0.07870	2.876	-21.66	0.06445	113.55
0.04937	3.218	-12.57	0.09082	123.65
0.04934	3.167	-12.82	0.09113	125.29
0.03096	3.166	- 3.84	0.1230	136.32
0.01787	3.008	1.53	0.1518	148.97
0.01796	3.260	0.10	0.1387	147.59
0.01134	3.162	3.53	0.1534	155.33
0.01755	3.222	0.50	0.1434	148.77
0.03030	3.239	- 4.78	0.1210	137.53
0.04880	3.197	-13.18	0.09020	124.95
0.07787	2.890	-22.41	0.06234	116.40
0.1292	2.320	-27.83	0.04033	111.14
0.2165	1.810	-28.00	0.02406	119.68
0.2170	1.815	-27.83	0.02517	117.29

TABLE V-7
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
2 MW, 40% Flow (Set #1, Series B)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5718	1.121	-12.97	0.002594	-126.00
0.9845	1.205	-15.92	0.003950	81.48
0.6150	1.316	-19.78	0.008442	85.62
0.6177	1.313	-20.07	0.006337	79.70
0.3585	1.526	-25.04	0.01453	85.52
0.2285	1.790	-28.05	0.02286	100.24
0.2301	1.798	-28.07	0.02316	95.35
0.1299	2.311	-28.24	0.03928	105.86
0.07791	2.904	-22.94	0.06057	112.88
0.04847	3.322	-13.95	0.08600	122.37
0.04852	3.316	-14.38	0.08498	122.73
0.02996	3.395	- 5.89	0.1127	135.28
0.01692	3.365	- 0.72	0.1345	148.84

TABLE V-8
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
2 MW, 40% Flow (Set #2 and #3, Series B)
Power Channel 28

<u>Frequency</u> <u>(rad/sec)</u>	<u>Power-Reactivity Transfer Function</u>		<u>Feedback Kernel</u>	
	<u>Amplitude</u> <u>(percent power)</u> <u>(cents reactivity)</u>	<u>Phase</u> <u>(degrees)</u>	<u>Amplitude</u> <u>(\$/MW)</u>	<u>Phase</u> <u>(degrees)</u>
0.9640	1.208	-16.38	0.002122	64.53
0.5925	1.328	-20.13	0.008951	82.86
0.5943	1.323	-20.13	0.008254	90.28
0.3335	1.559	-25.45	0.01629	91.90
0.2022	1.901	-28.51	0.02660	97.07
0.2028	1.894	-28.41	0.02666	98.73
0.1305	2.314	-28.50	0.03840	104.52
0.07900	2.906	-23.12	0.06004	111.62
0.04955	3.319	-14.47	0.08441	121.62
0.04964	3.302	-14.69	0.08409	122.16
0.03116	3.400	- 6.41	0.1106	134.18
0.01815	3.379	- 1.41	0.1318	147.47
0.01155	3.358	3.23	0.1444	153.94
1.5756	1.123	-12.73	0.001296	189.51
0.9876	1.207	-15.86	0.004678	71.96
0.6167	1.311	-19.92	0.006948	90.43
0.6181	1.300	-20.02	0.005774	115.83
0.3590	1.518	-24.92	0.01435	92.20
0.2277	1.799	-28.06	0.02332	98.03
0.2288	1.789	-27.84	0.02378	100.92

TABLE V-9
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
5 MW, 30% Flow (Set #1, Series A)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (<u>percent power</u>) (<u>cents reactivity</u>)	Phase (<u>degrees</u>)	Amplitude (<u>\$/MW</u>)	Phase (<u>degrees</u>)
1.579	1.151	-12.44	0.003970	25.04
0.9908	1.229	-15.16	0.005372	55.92
0.6201	1.343	-18.51	0.007800	71.91
0.3592	1.551	-22.12	0.01269	90.84
0.2280	1.859	-23.31	0.01906	95.85
0.1299	2.403	-16.96	0.03269	103.54
0.07819	2.773	- 0.81	0.05144	110.47
0.04881	2.511	15.00	0.07401	119.74
0.03058	1.943	21.04	0.1019	132.60
0.01764	1.604	18.27	0.1247	146.72
0.01116	1.530	14.81	0.1312	155.28

TABLE V-10
 POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
 5 MW, 30% Flow (Set #2, Series A)
 Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude ($\frac{\text{percent power}}{\text{cents reactivity}}$)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5751	1.147	-12.21	0.003683	38.52
0.9871	1.230	-15.10	0.005580	57.73
0.6138	1.345	-18.38	0.008247	74.89
0.3525	1.570	-22.34	0.01293	87.74
0.2192	1.894	-22.90	0.02035	96.57
0.1307	2.421	-17.05	0.03262	102.03
0.07890	2.774	- 1.09	0.05112	110.24
0.04925	2.522	15.09	0.07382	119.27
0.04939	2.469	16.18	0.07609	119.31
0.03063	1.973	20.67	0.1002	132.50
0.01758	1.603	14.69	0.1228	150.26
0.01116	1.536	14.85	0.1307	155.20

TABLE V-11
 POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
 5 MW 30%, Flow (Set #1 and #2, Series B)
 Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude ($\frac{\text{percent power}}{\text{cents reactivity}}$)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5397	1.140	-12.47	0.002110	51.80
0.9613	1.218	-15.32	0.004196	79.67
0.5941	1.340	-18.46	0.008083	87.87
0.3378	1.572	-22.37	0.01325	96.03
0.2098	1.902	-22.93	0.02045	101.20
0.1283	2.404	-16.67	0.03307	104.47
0.07729	2.734	- 0.99	0.05158	112.09
0.04826	2.452	15.34	0.07578	120.78
0.03028	1.950	20.50	0.1012	133.15
0.01755	1.609	15.38	0.1227	149.55
0.01089	1.604	16.30	0.1259	153.56
0.01739	1.612	16.89	0.1234	148.15
0.1291	2.388	-16.94	0.03267	104.95
0.9739	1.219	-15.05	0.004789	77.26

TABLE V-12
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
5 MW, 50% Flow (Set #1, Series A)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power) (cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5570	1.144	-13.13	0.002795	-6.81
0.9765	1.211	-15.80	0.002367	73.07
0.2105	1.893	-23.57	0.01920	101.41
0.1288	2.324	-16.96	0.03265	109.13
0.07795	2.627	- 1.95	0.05155	115.36
0.04858	2.375	12.65	0.07498	124.16
0.03032	1.951	17.53	0.09877	135.85
0.02996	1.939	16.89	0.09895	136.80
0.01082	1.562	17.52	0.1297	152.70

TABLE V-13
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
5 MW, 50% Flow (Set #2, Series A)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power) (cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5562	1.134	-13.14	0.001385	-31.31
0.9691	1.208	-15.94	0.001914	83.51
0.5996	1.319	-19.49	0.004645	98.44
0.3526	1.538	-22.90	0.01085	97.33
0.2179	1.851	-23.52	0.01867	103.69
0.1291	2.316	-17.12	0.03241	109.53
0.07770	2.630	- 2.19	0.05123	115.52
0.04866	2.395	12.52	0.07432	123.85
0.02930	1.924	17.70	0.1005	136.61
0.01656	1.672	16.67	0.1193	148.39
0.009925	1.542	17.69	0.1316	153.37

TABLE V-14
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
5 MW, 50% Flow (Set #1 and #2, Series B)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5198	1.133	-12.52	0.001517	92.12
0.9500	1.214	-15.33	0.004144	92.43
0.5879	1.340	-18.82	0.007331	88.53
0.3343	1.572	-22.42	0.01325	98.15
0.2065	1.902	-22.55	0.02121	103.58
0.1269	2.370	-16.69	0.03301	107.30
0.04776	2.436	12.04	0.07296	123.93
0.02969	2.024	17.42	0.09559	135.31
0.01698	1.760	16.44	0.1132	147.53
0.01052	1.654	18.45	0.1231	151.49
1.5376	1.133	-12.36	0.001826	82.63
0.5947	1.332	-18.57	0.007535	92.52
0.2078	1.910	-22.69	0.02101	101.60
0.07682	2.677	- 2.07	0.05087	114.49
0.02978	2.005	17.21	0.09619	135.70
0.01054	1.667	18.08	0.1220	151.75

TABLE V-15
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
5 MW, 100% Flow (Set #1, Series A)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power) (cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5510	1.110	-12.19	0.003541	156.55
0.9683	1.190	-15.27	0.004228	132.62
0.6050	1.300	-18.53	0.006967	117.51
0.3472	1.518	-22.13	0.01263	110.39
0.2182	1.816	-23.13	0.01917	109.92
0.1285	2.286	-18.16	0.03091	112.09
0.07754	2.643	- 5.02	0.04762	116.87
0.04852	2.505	8.78	0.06797	124.87
0.03026	2.126	16.14	0.09018	134.76
0.01750	1.805	17.57	0.1110	145.65
0.01108	1.664	18.12	0.1222	151.27

TABLE V-16
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
5 MW, 100% Flow (Set #2, Series A)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power) (cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
0.9768	1.187	-15.98	0.002521	160.73
0.6086	1.300	-19.33	0.004633	119.15
0.3509	1.525	-22.84	0.01081	104.77
0.2204	1.821	-23.60	0.01820	107.37
0.1286	2.290	-18.22	0.03081	111.76
0.07785	2.633	- 5.31	0.04738	117.21
0.04887	2.513	8.56	0.06752	124.70
0.03067	2.138	16.22	0.08967	134.28
0.01773	1.806	17.24	0.1106	145.78
0.01055	1.647	18.01	0.1235	151.93

TABLE V-17
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
5 MW, 100% Flow (Set #1 and #2, Series B)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5408	1.141	-12.42	0.002401	50.21
0.9664	1.218	-15.08	0.006727	81.65
0.6007	1.332	-18.45	0.007647	90.40
0.3449	1.558	-22.05	0.01339	97.27
0.2171	1.863	-22.73	0.02029	102.86
0.1285	2.326	-17.21	0.03228	109.24
0.07780	2.666	- 4.16	0.04844	115.53
0.03073	2.130	16.95	0.09056	133.70
0.01789	1.814	17.59	0.1103	145.26
0.01144	1.675	18.76	0.1215	150.29
1.5635	1.143	-12.34	0.002807	42.09
0.6145	1.329	-18.38	0.007368	86.64
0.2258	1.830	-22.80	0.01962	102.80
0.07825	2.669	- 4.44	0.04805	115.35
0.03090	2.147	16.85	0.08978	133.46
0.01161	1.655	19.18	0.1231	149.87

TABLE V-18
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
10 MW, 50% Flow (Set #1, Series A)
Power Channel 28

<u>Frequency</u> <u>(rad/sec)</u>	<u>Power-Reactivity Transfer Function</u>		<u>Feedback Kernel</u>	
	<u>Amplitude</u> <u>(percent power)</u> <u>(cents reactivity)</u>	<u>Phase</u> <u>(degrees)</u>	<u>Amplitude</u> <u>(\$/MW)</u>	<u>Phase</u> <u>(degrees)</u>
1.555	1.127	-11.66	0.001822	103.30
0.976	1.206	-14.19	0.003350	100.20
0.355	1.551	-18.69	0.01013	99.72
0.227	1.864	-16.87	0.01548	101.41
0.128	2.294	- 3.76	0.02693	106.73
0.077	2.205	15.71	0.04045	114.47
0.0484	1.724	26.10	0.05715	124.16
0.0303	1.336	26.60	0.07493	135.56
0.0175	1.148	22.96	0.08780	146.40
0.0110	1.067	23.87	0.09543	149.42

TABLE V-19
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
10 MW, 50% Flow (Set #2, Series A)
Power Channel 28

<u>Frequency</u> <u>(rad/sec)</u>	<u>Power-Reactivity Transfer Function</u>		<u>Feedback Kernel</u>	
	<u>Amplitude</u> <u>(percent power)</u> <u>(cents reactivity)</u>	<u>Phase</u> <u>(degrees)</u>	<u>Amplitude</u> <u>(\$/MW)</u>	<u>Phase</u> <u>(degrees)</u>
1.5707	1.132	-11.53	0.001951	89.72
0.6146	1.330	-16.72	0.005786	93.55
0.3559	1.561	-18.82	0.009992	96.80
0.2256	1.872	-16.55	0.01582	101.32
0.1296	2.301	- 4.08	0.02600	106.59
0.0785	2.217	15.18	0.03997	114.24
0.0493	1.749	26.11	0.05639	123.47
0.0311	1.368	26.43	0.07309	135.01
0.0182	1.168	23.18	0.08632	145.69
0.0118	1.080	22.73	0.09407	150.07

TABLE V-20
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
10 MW, 50% Flow (Set #1 and #2, Series B)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power) (cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5221	1.119	-11.60	0.002325	124.58
0.9491	1.201	-14.50	0.003270	113.01
0.5855	1.324	-17.13	0.005737	105.52
0.3333	1.571	-18.98	0.01041	103.21
0.2064	1.918	-16.11	0.01649	104.16
0.1271	2.266	- 4.52	0.02583	109.12
0.0767	2.205	14.38	0.03966	115.67
0.0480	1.767	24.81	0.05533	124.71
0.0300	1.375	25.60	0.07256	136.10
0.0173	1.188	22.43	0.08483	146.71
0.0104	1.079	23.11	0.09426	150.18
1.5438	1.125	-11.53	0.002122	109.04
0.5974	1.324	-16.96	0.005714	101.87
0.2095	1.910	-16.18	0.01639	103.68
0.0775	2.222	13.79	0.03907	115.46
0.0300	1.388	25.73	0.07196	135.82
0.0106	1.089	23.84	0.09356	149.57

TABLE V-21
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
10 MW, 100% Flow (Set #1, Series A)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power) (cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5223	1.119	-11.65	0.002271	126.37
0.9511	1.203	-14.36	0.003420	110.11
0.5891	1.331	-17.04	0.005816	100.10
0.3354	1.569	-21.55	0.007520	100.20
0.2099	1.883	-16.01	0.01652	106.22
0.1273	2.235	- 5.37	0.02535	110.76
0.0767	2.224	11.81	0.03785	117.12
0.0479	1.826	23.78	0.05325	124.65
0.0299	1.444	26.86	0.06980	134.06
0.0173	1.186	25.66	0.08587	143.58
0.0107	1.039	25.77	0.09837	147.91

TABLE V-22
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
10 MW, 100% Flow (Set #2, Series A)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power) (cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5525	1.127	-11.73	0.001730	104.77
0.9690	1.207	-14.12	0.003537	100.84
0.6003	1.328	-16.59	0.006165	99.53
0.3426	1.560	-18.65	0.01050	102.32
0.2125	1.889	-16.31	0.01622	104.56
0.1291	2.237	- 5.72	0.02507	110.15
0.0780	2.243	11.47	0.03738	116.47
0.0487	1.853	23.33	0.05229	124.34
0.0305	1.456	26.52	0.06904	134.00
0.0177	1.189	25.20	0.08545	143.78
0.0113	1.064	25.76	0.09603	147.47

TABLE V-23
POWER-REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
10 MW, 100% Flow (Set #1 and #2, Series B)
Power Channel 28

Frequency (rad/sec)	Power-Reactivity Transfer Function		Feedback Kernel	
	Amplitude (percent power) (cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
1.5441	1.131	-11.73	0.001797	95.45
0.9562	1.218	-14.22	0.003621	91.89
0.5856	1.341	-17.02	0.005989	96.16
0.3281	1.592	-18.72	0.01091	101.04
0.1979	1.929	-15.60	0.01708	106.57
0.0771	2.262	10.87	0.03680	116.79
0.0479	1.873	23.18	0.05178	124.39
0.0296	1.466	26.53	0.06869	134.17
0.0167	1.200	24.76	0.08473	144.63
0.0166	1.185	24.43	0.08573	145.10
0.0480	1.873	23.07	0.05172	124.46
0.1287	2.237	- 6.22	0.02469	110.50
0.3299	1.595	-18.85	0.01074	99.50
0.9607	1.208	-14.09	0.003677	102.13

TABLE V-24
**POWER REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
 15 MW, 60% Flow**

Frequency (rad/sec)	Power Reactivity Function		Feedback Kernel	
	Amplitude ($\frac{\text{percent power}}{\text{cents reactivity}}$)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
Set 1				
0.01110	0.912	27.31	0.07466	146.99
0.01764	1.034	25.31	0.06529	145.13
0.04886	1.489	27.42	0.04393	126.81
0.07807	1.896	19.52	0.03194	118.23
0.1290	2.136	3.30	0.02171	109.58
0.2196	1.865	-12.23	0.01327	104.23
0.3478	1.569	-16.57	0.00850	100.10
0.6052	1.324	-16.06	0.00450	100.45
0.9729	1.204	-13.76	0.00267	103.99
1.5545	1.124	-11.16	0.00174	108.76
Set 2				
0.0105	0.928	27.45	0.07342	146.78
0.0175	1.037	25.00	0.06508	145.46
0.0304	1.202	27.19	0.05403	136.71
0.0487	1.498	27.32	0.04367	126.80
0.0779	1.899	19.95	0.0329	117.87
0.1291	2.129	2.75	0.02147	110.12
0.2147	1.880	-11.58	0.01371	104.41
0.3440	1.579	-16.28	0.00879	99.69
0.6028	1.295	-16.16	0.00449	115.92
0.9726	1.211	-13.53	0.00292	96.89
1.5612	1.132	-11.27	0.00159	93.41

TABLE V-25
**POWER REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
 15 MW, 75% Flow, Series A**

Frequency (rad/sec)	Power Reactivity Function		Feedback Kernel	
	Amplitude ($\frac{\text{percent power}}{\text{cents reactivity}}$)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
Set 1				
0.01126	0.940	27.65	0.07249	146.41
0.01780	1.068	26.70	0.06349	143.39
0.03055	1.271	27.70	0.04102	135.27
0.04871	1.579	25.56	0.04102	127.02
0.07759	1.943	17.43	0.03047	119.01
0.1284	2.155	1.13	0.02073	111.76
0.2050	1.888	-11.91	0.01359	106.93
0.3351	1.573	-16.67	0.00862	103.23
0.5926	1.332	-16.07	0.00468	100.07
0.9597	1.205	-13.73	0.00281	104.88
1.5422	1.121	-11.36	0.00163	115.72
Set 2				
0.01149	0.951	27.98	0.07174	145.00
0.01807	1.068	26.38	0.06341	143.59
0.03095	1.279	27.79	0.05233	134.95
0.04917	1.575	26.09	0.04127	126.48
0.07847	1.947	17.05	0.03025	118.99
0.1295	2.117	1.36	0.02084	111.22
0.2143	1.866	-12.09	0.01341	105.75
0.3434	1.575	-16.39	0.00870	100.54
0.6014	1.328	-15.80	0.00479	99.84
0.9723	1.204	-13.64	0.00279	104.05
1.5545	1.130	-11.35	0.00154	98.62

TABLE V-26

POWER REACTIVITY TRANSFER FUNCTION AT
15 MW, 75% Flow, Series B

Frequency (rad/sec)	<u>Power Reactivity Transfer Function</u>		<u>Feedback Kernel</u>	
	Amplitude (%power per cents reactivity)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
.01133	.951	28.75	.07182	145.23
.01170	.965	27.67	.07069	146.03
.01771	1.087	26.20	.06237	143.75
.03058	1.296	27.00	.05151	135.60
.03117	1.301	26.81	.05121	135.51
.04867	1.593	25.11	.04056	127.21
.07763	1.971	16.46	.02973	119.15
.07845	1.973	16.13	.02955	119.13
.2168	1.861	-12.97	.01284	105.50
.2191	1.839	-13.04	.01279	106.67
.3445	1.566	-16.91	.008282	101.52
.6039	1.337	-16.07	.004580	94.94
.6155	1.322	-15.89	.004512	99.38
.9685	1.205	-13.81	.002654	103.59
.9828	1.198	-13.41	.002939	106.93
.9839	1.197	-13.56	.002777	107.85
1.5503	1.130	-11.43	.001471	97.41
1.5686	1.118	-11.04	.001846	115.80

TABLE V-27
POWER REACTIVITY TRANSFER FUNCTION AND FEEDBACK KERNEL AT
17 MW

Frequency (rad/sec)	Power Reactivity Transfer Function		Feedback Kernel	
	Amplitude ($\frac{\text{percent power}}{\text{cents reactivity}}$)	Phase (degrees)	Amplitude (\$/MW)	Phase (degrees)
Set 1				
0.0111	0.922	29.52	0.06351	144.78
0.0175	1.050	27.87	0.05555	142.56
0.0304	1.266	28.02	0.04537	135.07
0.0487	1.557	25.32	0.03555	127.61
0.0779	1.890	16.59	0.02642	120.85
0.1291	2.035	2.10	0.01863	114.01
0.3536	1.549	-15.77	0.00768	102.32
0.6137	1.322	-15.33	0.00431	99.95
0.9836	1.205	-13.27	0.00263	100.68
1.5715	1.124	-11.02	0.00154	104.88
Set 2				
0.0114	0.929	29.66	0.06306	144.45
0.0179	1.058	28.13	0.05517	142.05
0.0308	1.259	27.96	0.04558	135.09
0.0492	1.567	25.26	0.03531	127.38
0.0784	1.889	16.48	0.02638	120.82
0.1295	2.031	2.01	0.01861	114.08
0.2145	1.838	-10.75	0.01226	107.59
0.3428	1.564	-15.56	0.00797	102.90
0.6032	1.331	-15.33	0.00449	98.93
0.9734	1.204	-13.39	0.00259	103.66
1.5621	1.126	-11.06	0.00154	104.42

TABLE V-28

POWER REACTIVITY TRANSFER FUNCTION
AND FEEDBACK KERNEL AT 19 MW

<u>Frequency</u> (rad/sec)	<u>Power-Reactivity</u> <u>Transfer Function</u>		<u>Feedback Kernel</u>	
	<u>Amplitude</u> (%Power per cents reactivity)	<u>Phase</u> (degrees)	<u>Amplitude</u> (\$/MW)	<u>Phase</u> (degrees)
0.0114	0.913	27.567	.05887	146.6
0.0179	1.031	25.939	.05174	144.4
0.0309	1.215	25.531	.04289	138.0
0.0489	1.482	23.893	.03387	130.2
0.0781	1.798	17.206	.02559	122.4
0.1283	2.007	3.215	.01778	114.5
0.2228	1.805	-11.219	.01103	108.0
0.2241	1.821	-10.852	.01117	106.2
0.2244	1.862	-11.306	.01090	102.9
0.3500	1.590	-15.915	.00712	96.3
0.3506	1.530	-15.751	.00711	106.6
0.5590	1.349	-15.394	.00418	92.3
0.6053	1.320	-15.494	.00393	102.8
0.6128	1.324	-15.043	.00418	100.0
0.9539	1.225	-13.656	.00239	89.0
0.9648	1.195	-13.446	.00243	112.7
1.5153	1.130	-11.236	.00145	104.8
1.5393	1.119	-11.333	.00135	120.2
1.5622	1.121	-11.287	.00126	114.4

TABLE V-29
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 5 MW-30% Flow
 Series A

Frequency (rad/sec)	Set 1 $\Delta T_c/\Delta P$ (° F/MW)		Frequency (rad/sec)	Set 2 $\Delta T_c/\Delta P$ (° F/MW)	
	Real	Imaginary		Real	Imaginary
0.01116	4.6	-2.0	0.0112	4.6	-2.0
0.01764	4.7	-3.0	0.0176	4.8	-2.3
0.03058	2.8	-4.0	0.0306	2.6	-3.6
0.04881	0.9	-3.3	0.0494	1.2	-3.8
0.07819	-0.3	-2.4	0.0493	1.1	-3.5
0.1299	-0.7	-1.5	0.0789	0.0	-2.4
0.2280	-0.8	-0.5	0.1307	-1.2	0
0.3592	-0.3	-0.3	0.2192	2.0	-1.3
0.6201	-0.2	-0.2	0.3525	-0.7	-0.2
0.9908	-0.1	0.3	0.6138	1.7	-0.3
1.5790	0.0	0.0	0.9871	0	-0.1
			1.5751	-0.7	-1.4

TABLE V-30
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 5 MW—30% Flow
 Series B
 Sets 1 & 2

Frequency (rad/sec)	$\Delta T_c/\Delta P$ (° F/MW)	
	Real	Imaginary
0.01089	4.8	-3.0
0.01739	4.8	-3.2
0.01755	5.3	-2.9
0.03028	3.4	-3.7
0.04826	2.0	-3.5
0.07729	0.8	-2.8
0.1283	0.6	-1.8
0.1291	0.1	-2.0
0.2098	0.0	0.0
0.3378	0.0	0.0
0.5941	0.0	0.0
0.9613	0.0	0.0
0.9739	0.0	0.0
1.5397	0.0	0.0

TABLE V-32
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 5 MW—50% Flow
 Series A

Frequency (rad/sec)	Set 1 $\Delta T_c/\Delta P$ (° F/MW)		Frequency (rad/sec)	Set 2 $\Delta T_c/\Delta P$ (° F/MW)	
	Real	Imaginary		Real	Imaginary
0.01082	0.7	-6.5	0.009925	1.9	-4.0
0.02996	2.0	-4.4	0.01656	2.0	-3.0
0.03032	1.9	-3.4	0.02930	1.8	-2.9
0.04858	1.3	-3.2	0.04866	1.0	-3.2
0.07795	3.4	-3.2	0.07770	0.3	-2.7
0.1288	1.5	-2.7	0.1291	0.1	-2.1
0.2105	1.9	-5.2	0.2179	0.2	-2.4
0.9765	2.3	-2.5	0.3526	0.3	-2.2
1.5570	3.8	-3.0	0.5996	0.6	-1.7
			0.9691	0.6	-1.8
			1.5562	1.5	-1.6

TABLE V-31
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 5 MW-50% Flow
 Series B
 Sets 1 & 2

Frequency (rad/sec)	$\Delta T_c / \Delta P$ (°F/MW)	
	Real	Imaginary
0.01054	2.4	-3.0
0.01053	2.6	-3.0
0.01698	2.6	-2.3
0.02969	2.3	-2.0
0.02978	2.5	-2.0
0.04776	1.5	-2.0
0.07682	0.8	-1.9
0.1269	0.3	-1.3
0.2065	0.0	-1.0
0.2078	0.0	0.0
0.3343	-0.4	-0.7
0.5879	0.0	0.0
0.5947	0.0	0.0
0.9500	0.0	0.0
1.5198	0.0	0.0
1.5376	0.0	0.0

TABLE V-33
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 5 MW-100% Flow
 Series A

Frequency (rad/sec)	Set 1 $\Delta T_c / \Delta P$ (°F/MW)		Frequency (rad/sec)	Set 2 $\Delta T_c / \Delta P$ (°F/MW)	
	Real	Imaginary		Real	Imaginary
0.01108	1.2	-2.4	0.01055	-0.2	-4.9
0.01750	0.9	-1.8	0.01773	-0.5	-2.9
0.03026	0.7	-1.2	0.03067	-0.4	-1.8
0.04352	0.3	-1.4	0.04887	-0.4	-1.5
0.07754	0.4	-0.7	0.07785	0.3	-1.6
0.1288	0.2	-1.0	0.1286	0.2	-1.7
0.2182	-0.1	-0.5	0.2024	0.7	-3.4
0.3472	0.1	-0.2	0.3509	1.0	-3.1
0.6050	-0.1	-0.1	0.6086	0.3	-3.0
0.9683	0.0	0.1	0.9768	0.4	-2.6
1.551	0.0	0.2			

TABLE V-34
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 5 MW—100% Flow
 Series B
 Sets 1 & 2

Frequency (rad/sec)	$\Delta T_c/\Delta P$ (° F/MW)	
	Real	Imaginary
0.01144	1.4	-5.5
0.01161	2.6	-5.1
0.01789	1.0	-3.2
0.03073	0.6	-2.1
0.03090	0.4	-2.2
0.07780	0.2	-1.2
0.07825	0.3	-1.1
0.1285	0.1	-0.8
0.2171	0.0	-0.4
0.2258	0.0	-0.5
0.3449	0.0	-0.3
0.6145	0.2	-0.4
1.5635	0.1	-0.1

TABLE V-35
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 10 MW—50% Flow
 Series A

Frequency (rad/sec)	Set 1 $\Delta T_c/\Delta P$ (° F/MW)		Frequency (rad/sec)	Set 2 $\Delta T_c/\Delta P$ (° F/MW)	
	Real	Imaginary		Real	Imaginary
0.01103	1.0	-4.1	0.01176	1.4	-3.8
0.01758	2.1	-2.2	0.01825	1.8	-2.6
0.03030	2.3	-1.9	0.03108	2.4	-1.7
0.04842	1.6	-2.1	0.04931	1.5	-2.2
0.07739	0.9	-1.9	0.07853	0.8	-1.9
0.1284	0.8	-1.0	0.1296	0.2	-1.4
0.2266	-0.3	-1.0	0.2250	-0.2	-1.1
0.3553	-0.5	-0.3	0.3559	-0.3	-0.5
0.9760	-0.2	-0.2	0.6146	-0.3	0
1.5550	-0.2	0.1	1.5707	0.2	0

TABLE V-36
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 10 MW-50% Flow
 Series B
 Sets 1 & 2

Frequency (rad/sec)	$\Delta T_c/\Delta P$ (° F/MW)	
	Real	Imaginary
0.01056	1.4	-4.0
0.01085	1.6	-4.0
0.01726	1.7	-2.0
0.02995	2.2	-1.6
0.02998	2.2	-1.6
0.04020	1.7	-1.8
0.07668	1.0	-1.8
0.07746	1.6	1.2
0.1271	-0.4	-1.5
0.2064	-0.0	-1.1
0.2095	0.1	-1.0
0.3333	-0.4	-0.8
0.5855	-0.3	-0.2
0.5974	-0.3	-0.2
0.9491	-0.1	0.1
1.5221	-0.1	0.2
1.5938	0.1	0.0

TABLE V-37
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 10 MW-100% Flow
 Series A

Frequency (rad/sec)	Set 1 $\Delta T_c/\Delta P$ (° F/MW)		Frequency (rad/sec)	Set 2 $\Delta T_c/\Delta P$ (° F/MW)	
	Real	Imaginary		Real	Imaginary
0.01071	0.8	-5.1	0.01128	0.8	-4.9
0.01729	0.0	-2.7	0.01773	0.2	-2.8
0.02990	0.2	-1.2	0.03046	0.4	-1.3
0.04794	0.6	-0.8	0.04866	0.6	-1.0
0.0767	0.6	-0.8	0.07803	0.6	-0.9
0.1273	0.5	-0.7	0.1291	0.5	-0.7
0.2099	0.1	-0.6	0.2125	0.0	-0.6
0.3354	0.0	-0.4	0.3426	-1.2	-0.8
0.5891	-0.2	-0.3	0.6003	-1.6	-0.8
0.9511	-0.2	-0.1	0.9690	-0.3	0
1.5223	-0.1	0.2	1.5525	-0.2	0

TABLE V-38
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 10 MW-100% Flow
 Series B
 Set 1 & 2

Frequency (rad/sec)	$\Delta T_c/\Delta P$ (°F/MW)	
	Real	Imaginary
0.01665	0.5	-2.4
0.01667	0.4	-2.4
0.02964	0.5	-1.3
0.04785	0.4	-0.7
0.04795	0.5	-0.8
0.07706	0.5	-0.6
0.1287	0.4	-0.6
0.1979	0.2	-0.6
0.3281	0.1	-0.5
0.3299	0.0	-0.4
0.5856	-0.2	-0.2
0.9562	-0.3	-0.1
0.9607	0.0	-0.2
1.5441	-0.3	0.0

TABLE V-39
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 15 MW-60% Flow
 Series A

Frequency (rad/sec)	Set 1 $\Delta T_c/\Delta P$ (°F/MW)		Frequency (rad/sec)	Set 2 $\Delta T_c/\Delta P$ (°F/MW)	
	Real	Imaginary		Real	Imaginary
0.0111	1.5	-4.0	0.01105	1.3	-3.8
0.01764	1.2	-2.5	0.01751	1.2	-2.2
0.04886	1.6	-1.5	0.03039	1.7	-1.4
0.07807	1.1	-1.5	0.04869	1.6	-1.4
0.1290	0.4	-1.3	0.07789	1.0	-1.5
0.2196	-0.8	-1.0	0.1291	-0.5	-1.4
0.3477	-0.3	-0.6	0.2147	-0.1	-0.9
0.6052	-0.3	-0.2	0.3440	-0.2	-0.7
0.9729	-0.1	0.1	0.6028	-0.1	-0.3
1.5545	0.2	0.3	0.9726	-0.2	-0.1
			1.5612	-0.0	0.1

TABLE V-40
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 15 MW-75% Flow
 Series A

Frequency (rad/sec)	Set 1 $\Delta T_c/\Delta P$ (° F/MW)		Frequency (rad/sec)	Set 2 $\Delta T_c/\Delta P$ (° F/MW)	
	Real	Imaginary		Real	Imaginary
0.01126	1.1	-4.1	0.01149	1.7	-2.6
0.01780	1.0	-2.3	0.01807	1.2	-1.4
0.03055	1.0	-1.1	0.03095	1.5	-1.4
0.04871	1.2	-1.1	0.04917	1.2	-1.2
0.07759	0.9	-1.1	0.07847	0.9	-1.1
0.1284	0.5	-0.7	0.1295	0.5	-1.0
0.2050	0.2	-0.6	0.2143	0.2	-0.8
0.3351	-0.1	-0.3	0.3434	0.0	-0.6
0.5926	-0.1	-0.1	0.6014	-0.2	-0.3
0.9597	-0.1	-0.1	0.9723	-0.2	0.0
1.5422	0.0	0.0	1.5545	-0.1	-0.1

TABLE V-41

AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTION AT
15 MW, 75% Flow, Series B

Frequency (rad/sec)	$\Delta T_c / \Delta P$ (°F/MW)	
	Real	Imaginary
.01133	1.0	-4.3
.01170	1.2	-4.3
.01771	0.8	-2.4
.03058	1.0	-1.3
.03117	1.0	-1.1
.04867	1.1	-0.9
.07763	1.0	-1.1
.07845	1.0	-1.1
.2168	0.2	-0.9
.2191	0.2	-0.8
.3445	-0.1	-0.6
.6039	-0.1	-0.3
.6155	-0.2	-0.3
.9685	-0.2	-0.1
.9828	-0.2	-0.1
.9839	-0.2	-0.1
1.5503	0.0	0.0
1.5686	0.0	0.0

TABLE V-42
 AVERAGE COOLANT TEMPERATURE TO POWER TRANSFER FUNCTIONS AT
 17 MW-75% Flow
 Series A

Frequency Rad/sec)	Set 1 $\Delta T_c/\Delta P$ (° F/MW)		Frequency (rad/sec)	Set 2 $\Delta T_c/\Delta P$ (° F/MW)	
	Real	Imaginary		Real	Imaginary
0.01106	0.6	-3.5	0.01140	0.6	-3.6
0.01748	0.5	-2.2	0.01792	0.5	-2.2
0.0304	0.6	-1.3	0.03079	0.6	-1.1
0.04872	0.8	-0.8	0.04917	0.7	-0.8
0.07787	0.7	-0.7	0.07843	0.7	-0.7
0.1291	0.5	-0.8	0.1295	0.5	-0.8
0.3536	0.0	-0.6	0.2145	0.2	-0.7
0.6137	-0.2	-0.2	0.3428	0.0	-0.5
0.9836	-0.1	-0.2	0.6032	-0.1	-0.3
1.5715	-0.2	0	0.9734	-0.2	0.0
			1.5621	-0.1	0.0

TABLE V-43

AVERAGE COOLANT TEMPERATURE TO POWER
TRANSFER FUNCTION AT 19 MW

Frequency (rad/sec)	$\Delta T_c / \Delta P$ ($^{\circ}\text{F}/\text{MW}$)	
	Real	Imaginary
0.0114	1.5	-3.8
0.0179	1.2	-2.4
0.0309	1.1	-1.2
0.0489	1.1	-0.6
0.0781	0.1	-0.8
0.1283	0.7	-1.0
0.2228	0.2	-1.1
0.2241	0.1	-1.1
0.2244	-0.1	-1.2
0.3500	-0.1	-0.9
0.3506	-0.1	-0.8
0.5990	-0.2	-0.4
0.6053	-0.1	-0.4
0.6128	-0.1	-0.4
0.9539	-0.2	-0.1
0.9648	0.0	-1.0
1.5153	0.0	0.0
1.5393	0.0	0.0
1.5622	0.2	0.0

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